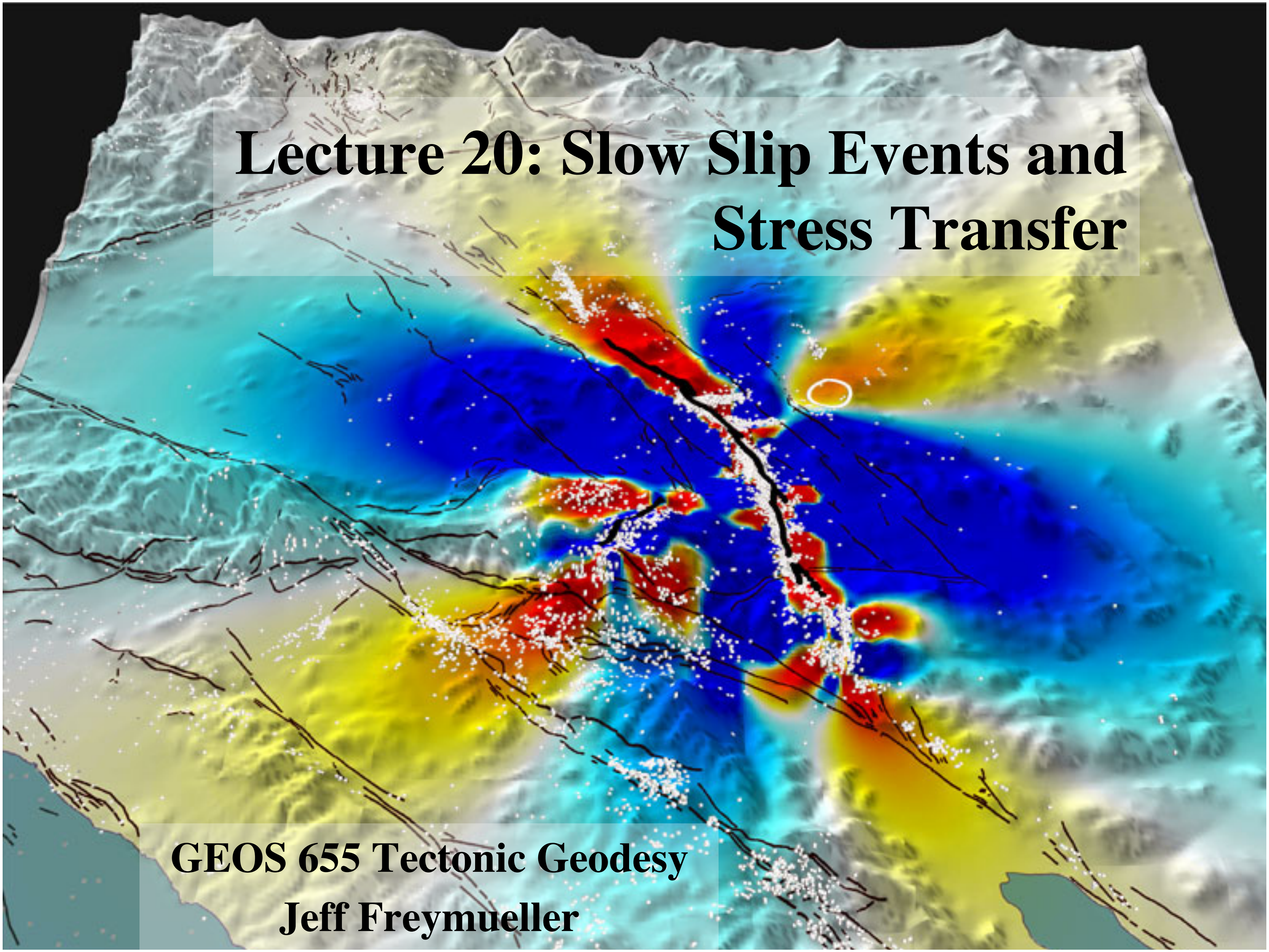
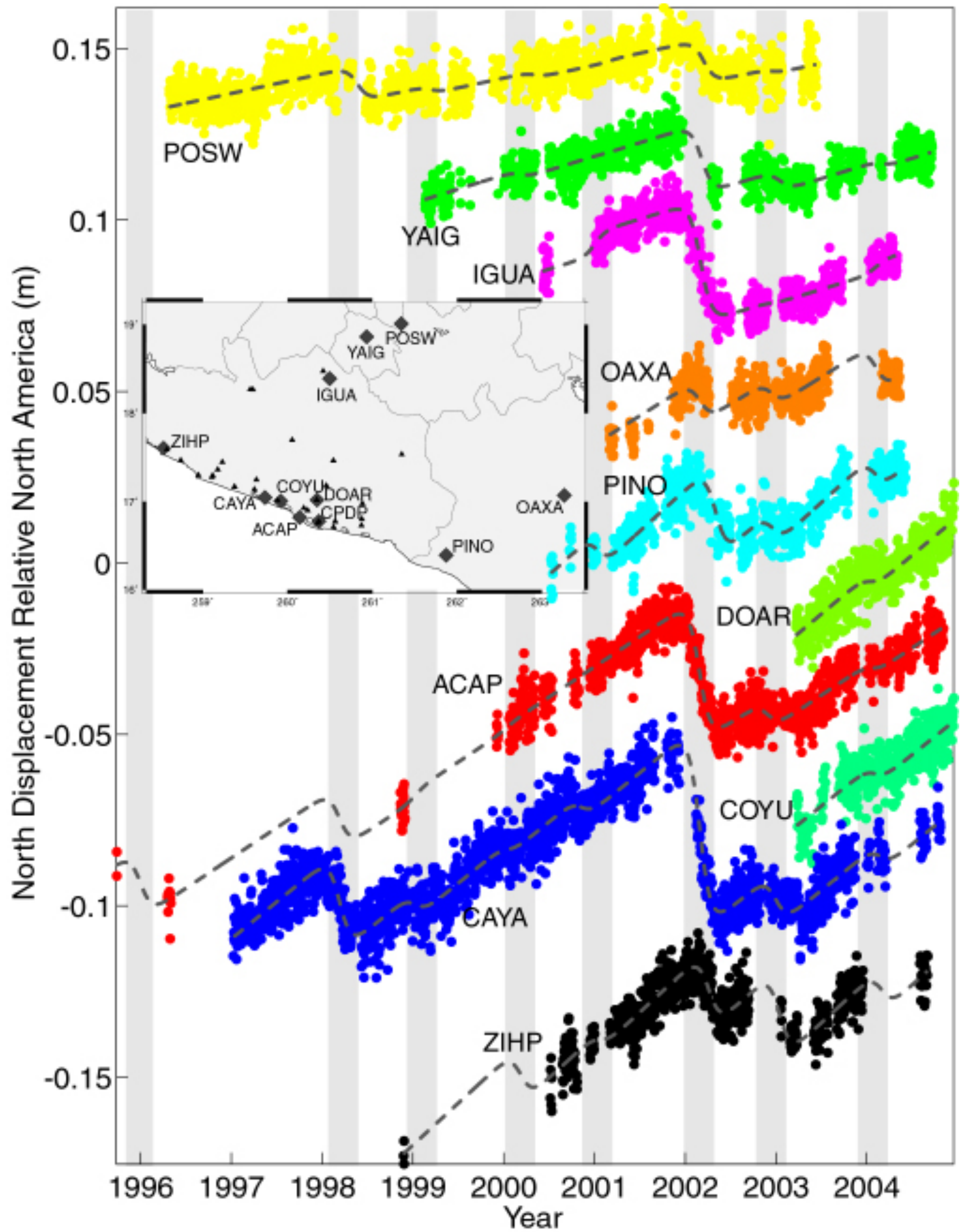
Lecture 20: Slow Slip Events and Stress Transfer



GEOS 655 Tectonic Geodesy

Jeff Freymueller

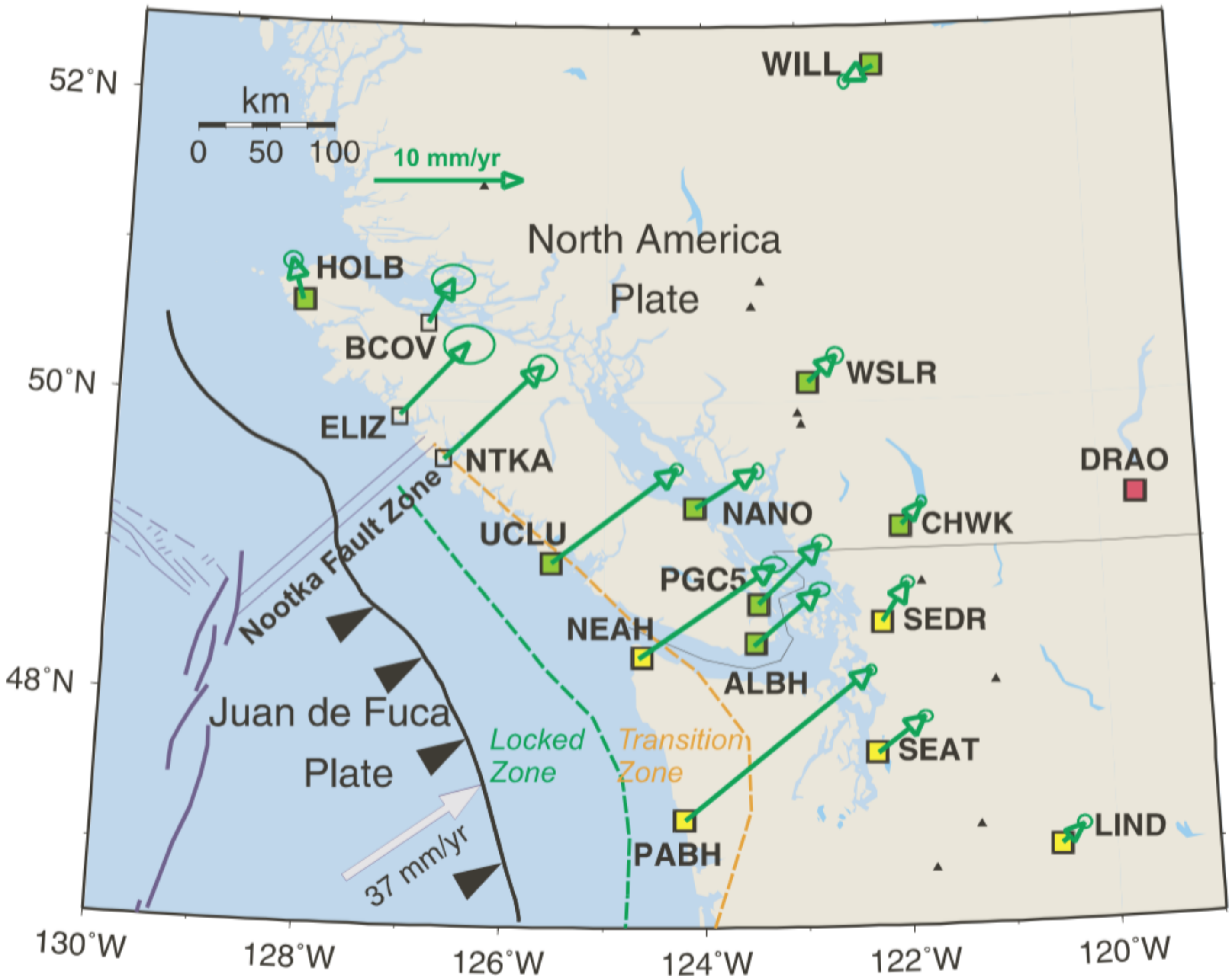


Slow Slip Events

Signal of interseismic strain accumulation

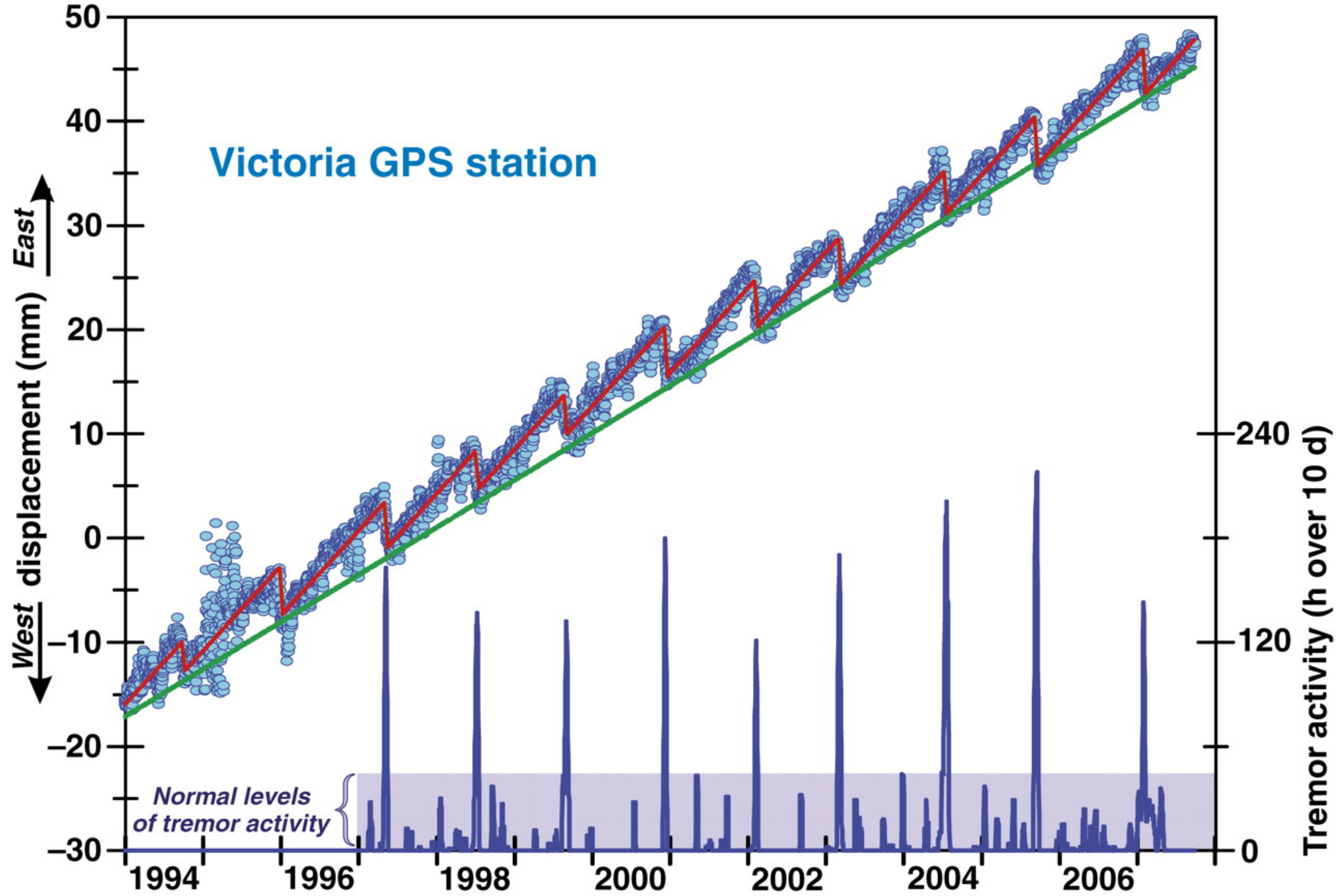
From Kristine Larson

Cascadia Velocities



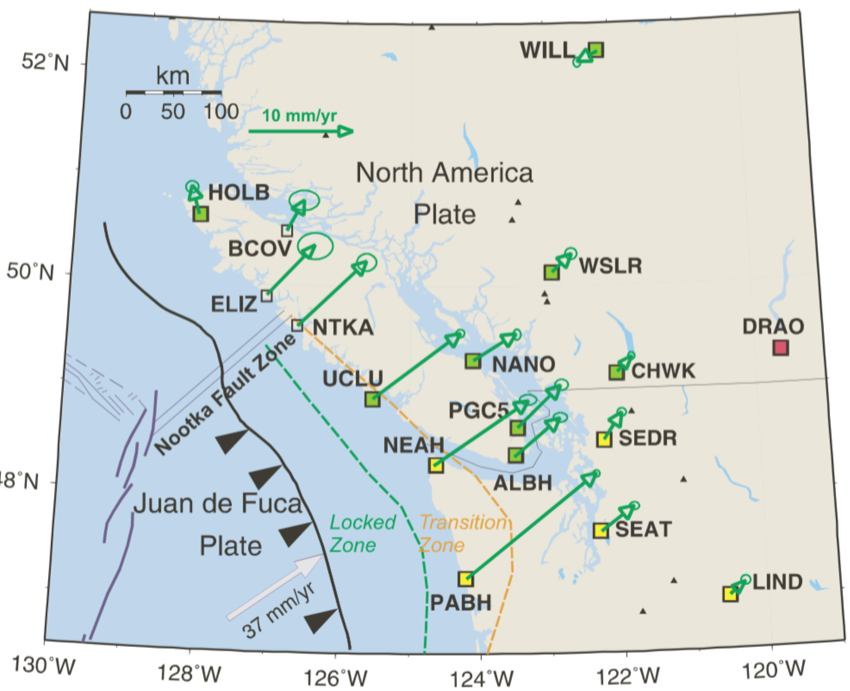
Dragert et al. (2004)

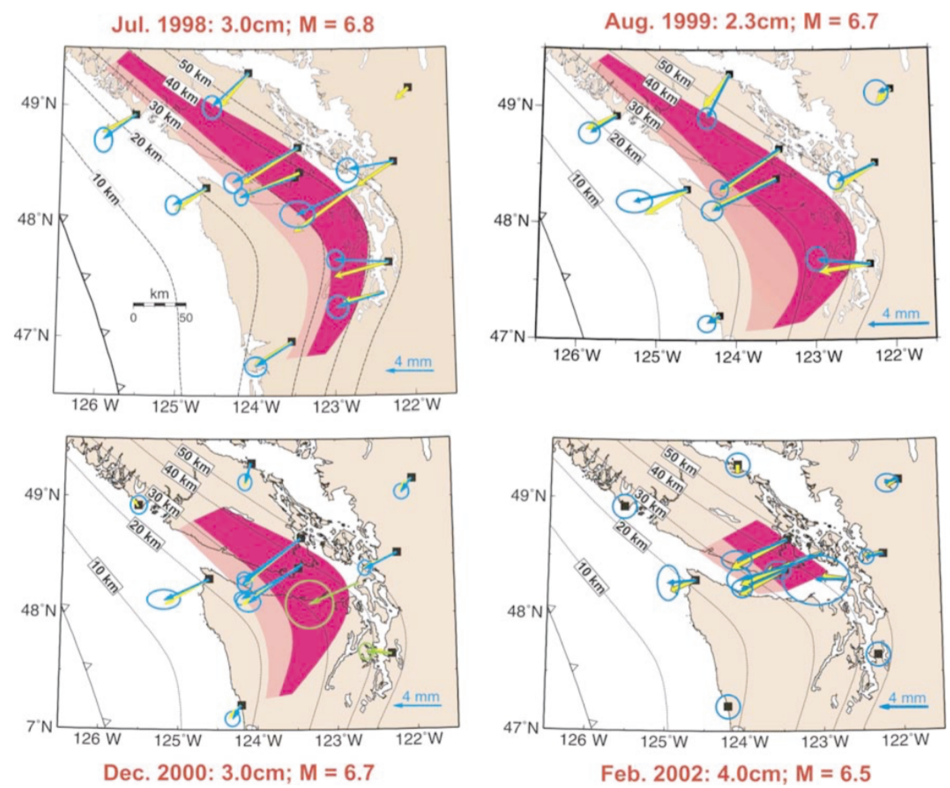
Repeated Slow Slip (Cascadia)



Gomberg et al. (2010)

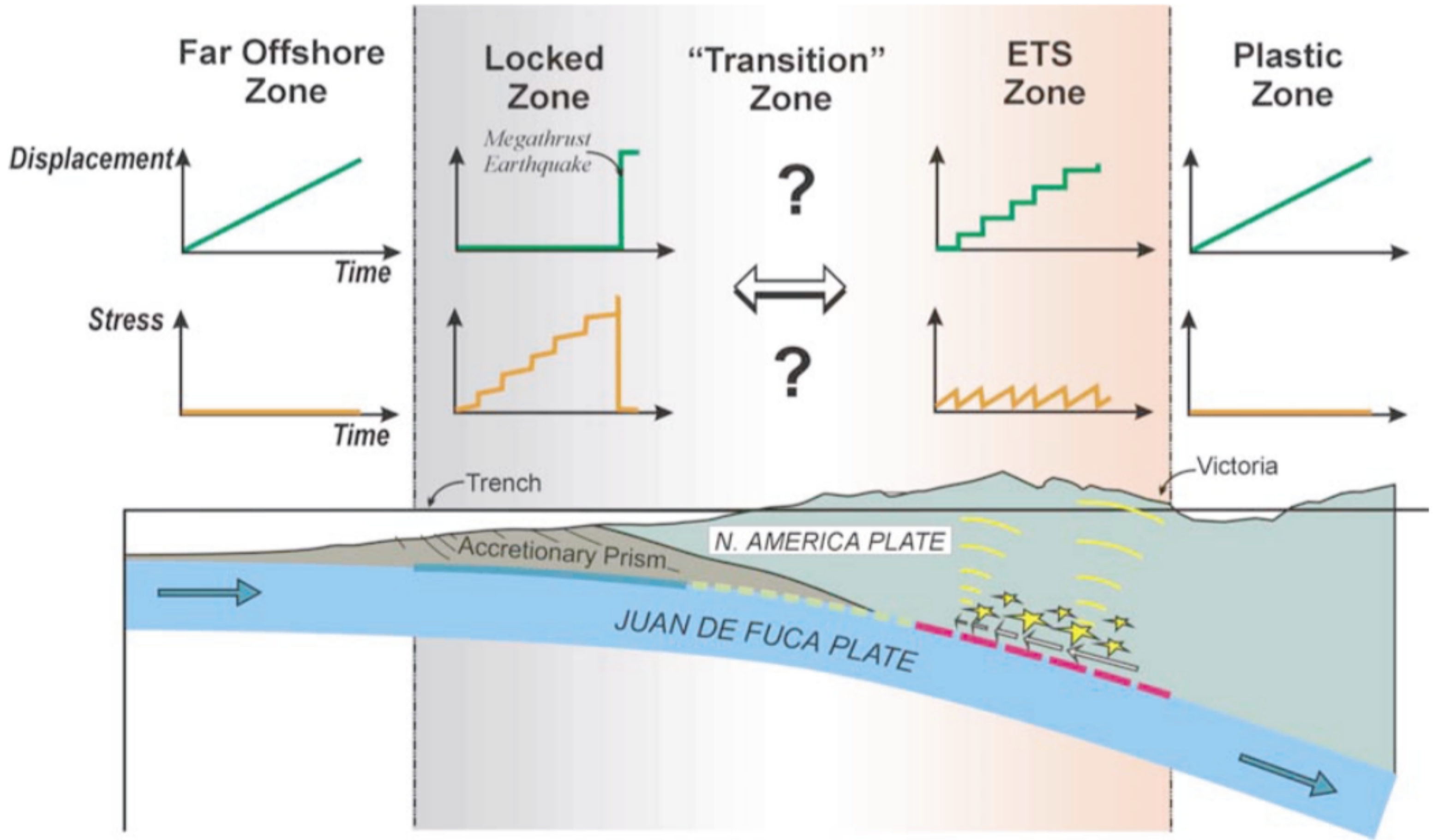
Long term vs Slow Slip Event





Dragert et al. (2004)

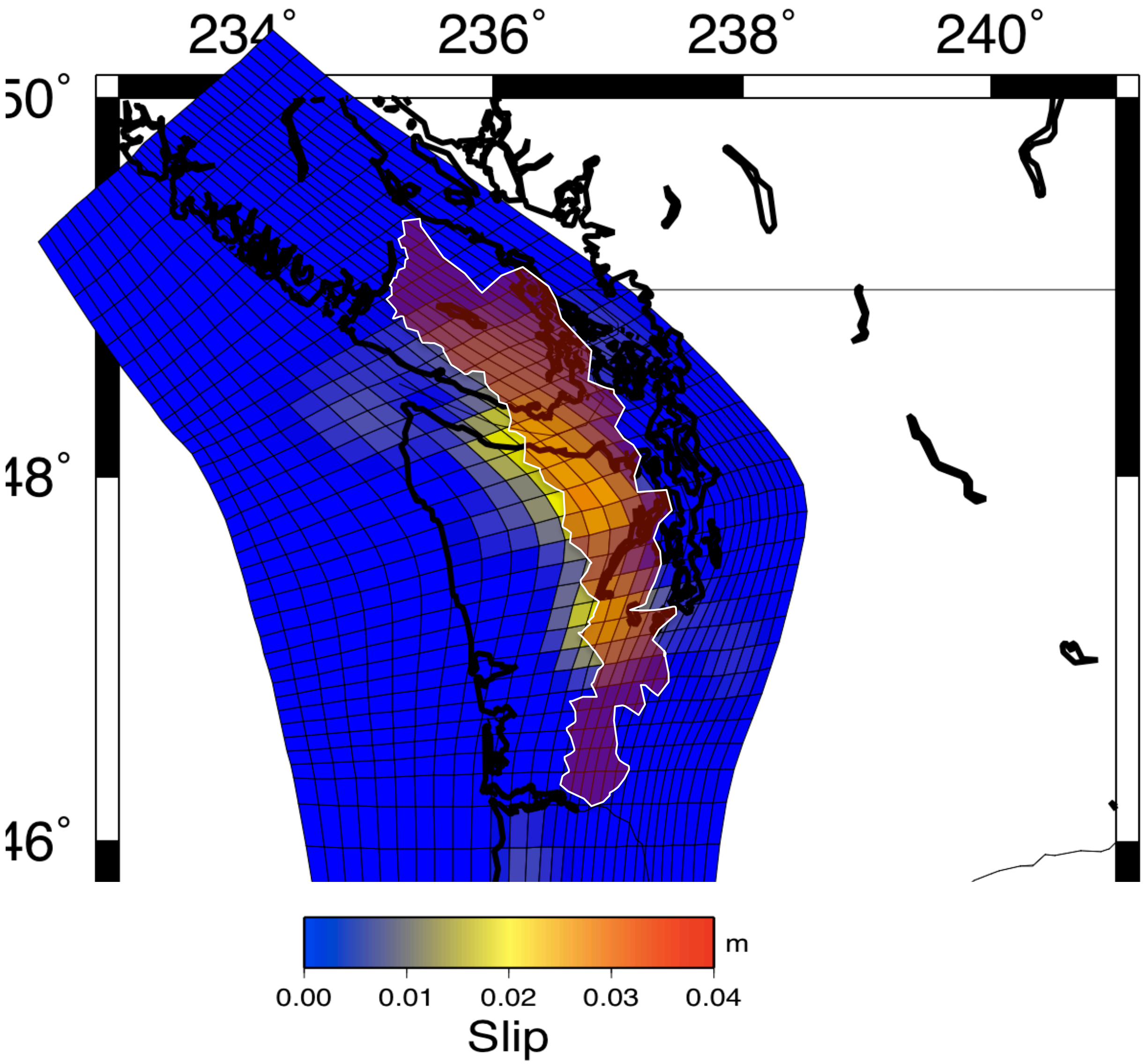
Where do Slow Events Occur?

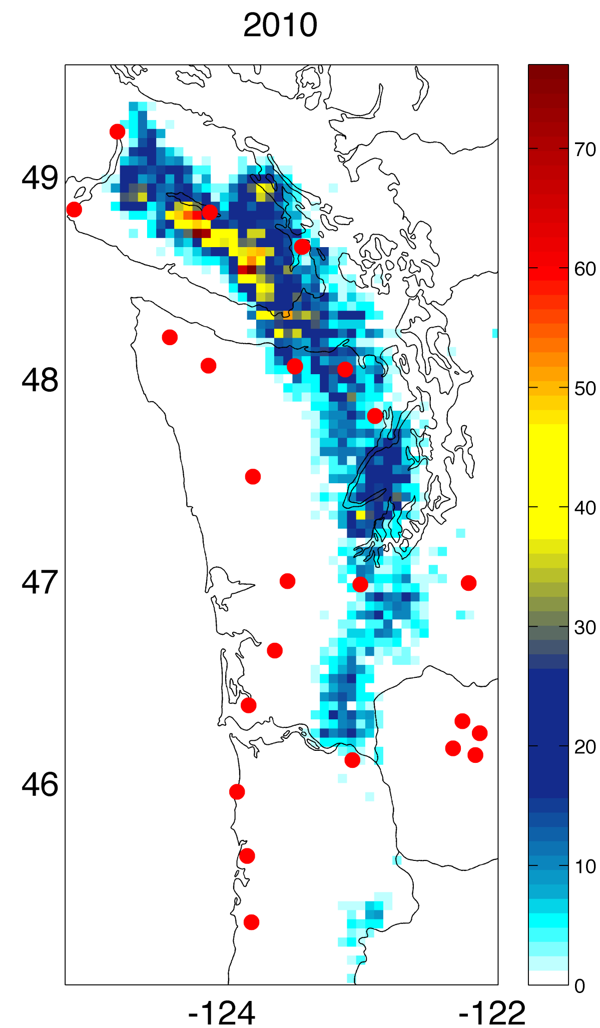


Dragert et al. (2004)

Relationship of Slow Slip and Tremor

Slide from Heidi Houston, UW





Melbourne

Similar results from Schmidt and Krogstad

Delbridge and Houston

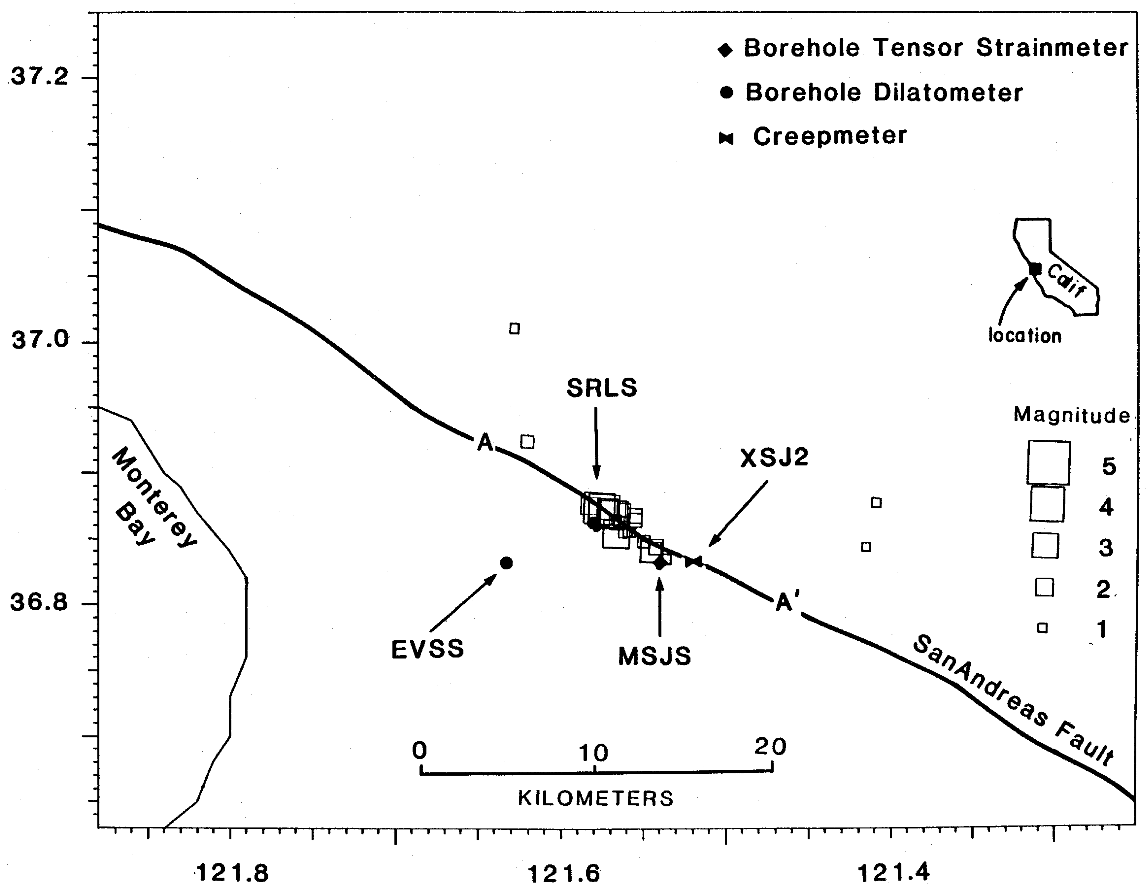
What is a Slow Slip Event?

- Slip on a fault, like in an earthquake, BUT
  - Slow: hours to years rather than seconds
  - Releases little high-frequency seismic energy, so it is sometimes called a type of aseismic slip.
  - However, many or most of these events do produce a tremor-like seismic signal.
  - Discrete events, rather than continuous creep/slip
- Probably frictionally controlled slip, but not unstable like seismic slip
  - conditional stability from rate and state friction?
- Now known to be very common at and below base of main seismogenic zone at subduction zones.

Older Slow Slip Events

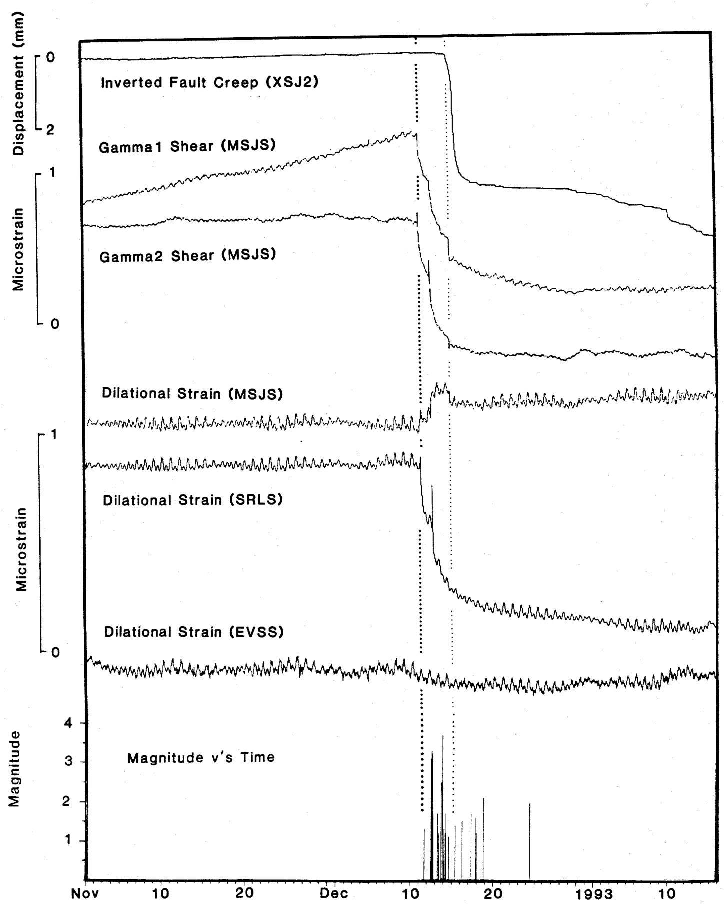
- Not generally accepted as real until ~15-20 years ago.
- Suggestion of a slow precursor before 1960 Chile earthquake (a few minutes prior)
- Slow Slip Before 1944 Tonankai, 1946 Nankaido earthquakes
  - Survey misclosures, tide gauges, water well level changes prior to each earthquake
  - Investigated as possible earthquake precursors
  - Linde and Sacks (2002) showed that observations were consistent with slow slip on plate interface below main seismogenic zone.
- Some "Silent Earthquakes" identified through normal modes; some did not correspond to regular quakes

San Juan Bautista 1993

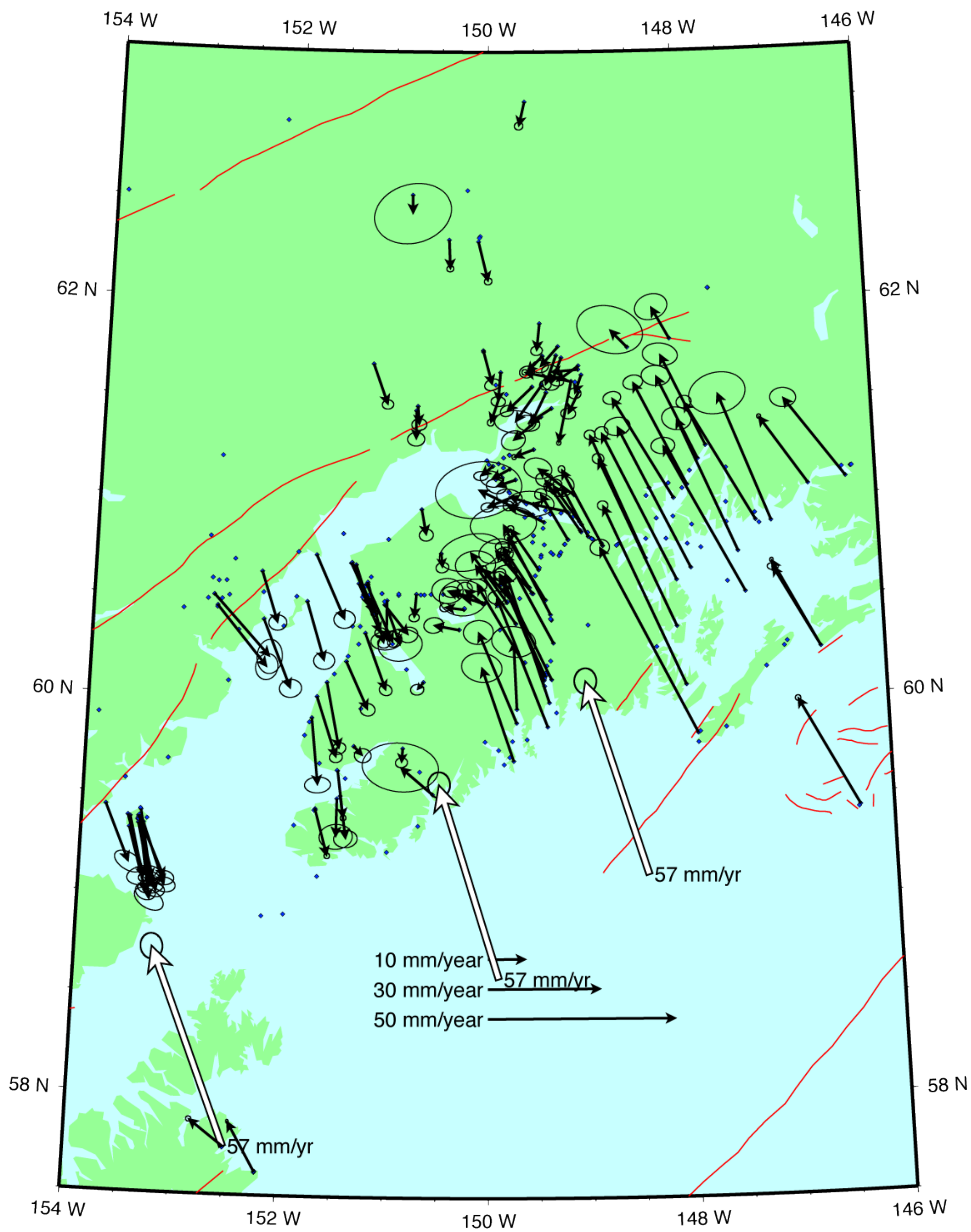


M. Johnston, USGS

"Mostly Silent" Earthquake

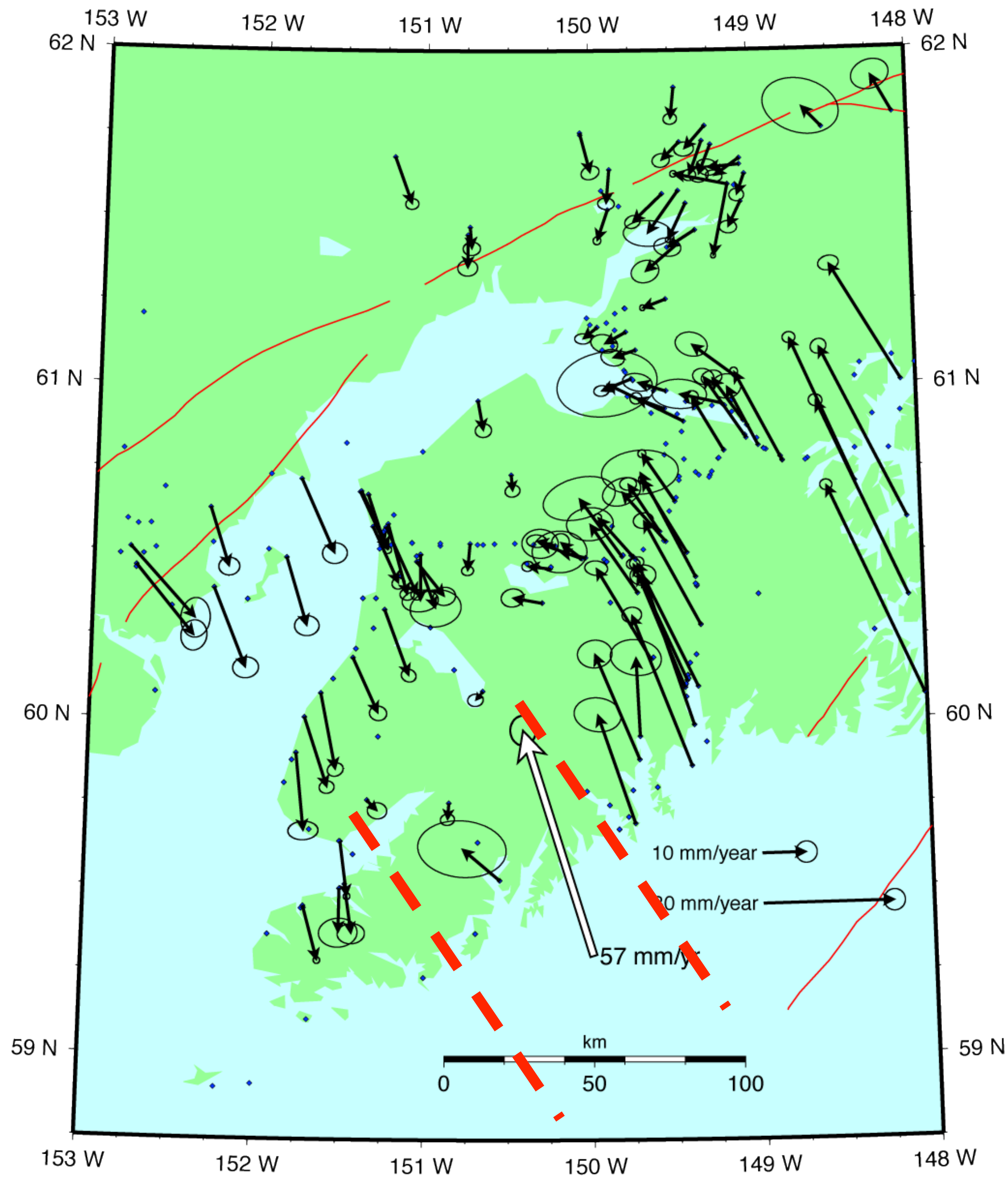


- Significant fault creep and near-fault strain accompanied swarm of small earthquakes
- Creep and strain too large to explain by earthquakes
- Interpretation is that a patch on the fault was creeping
- What triggered what?



Kenai

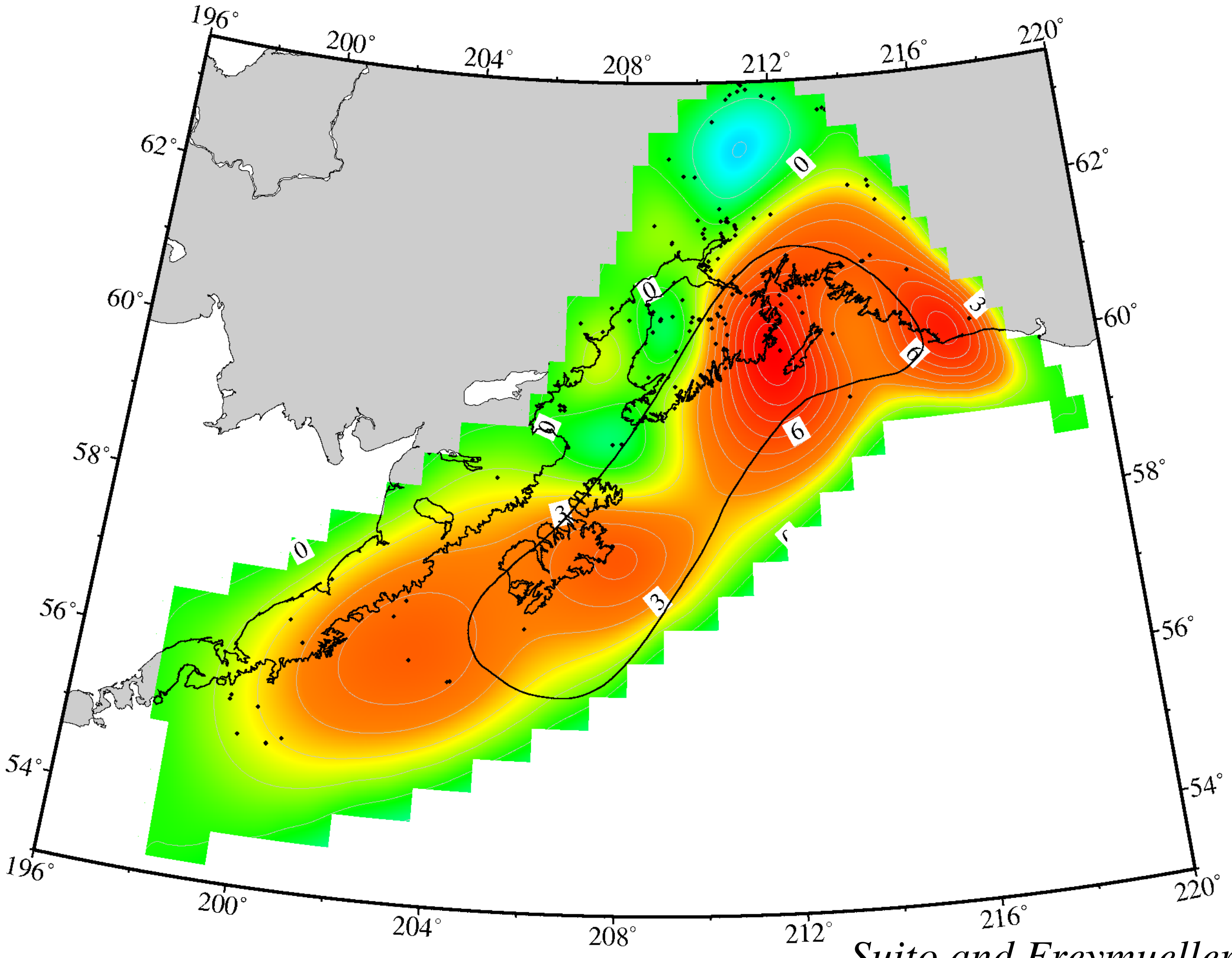
- Combination of
  - locked subduction zone (NNW)
  - postseismic deformation (SSE)
- Up to 55 mm/yr relative to NOAM
- Up to ~75 mm/yr relative motions
- Along-strike changes in seismogenic zone



Kenai Detail

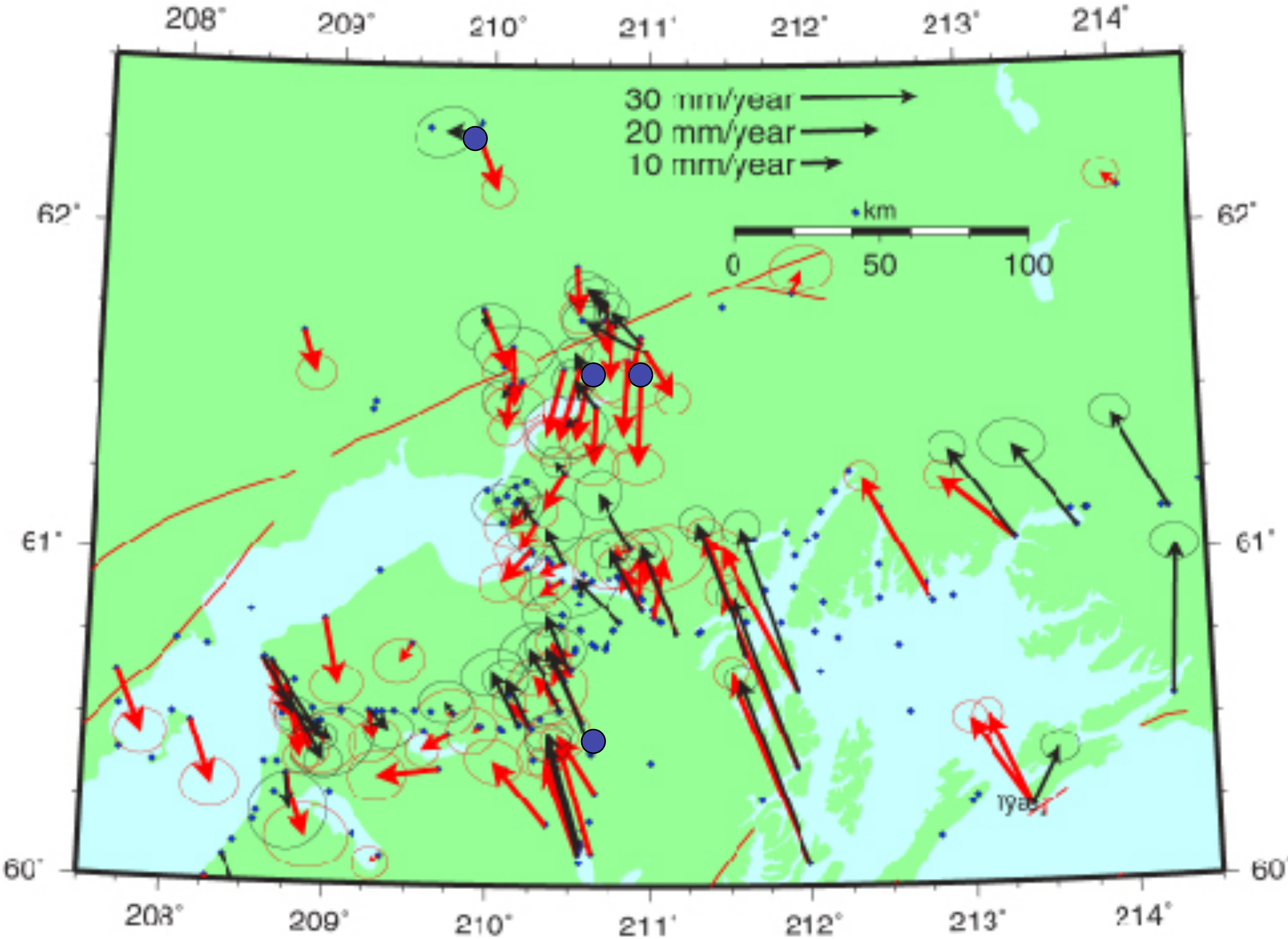
- Obvious transition between western and eastern Peninsula
- Look at sites same distance from trench
- Edge of plate coupling toward western edge of Peninsula
  - Edge of PWS asperity

Regional Plate Coupling

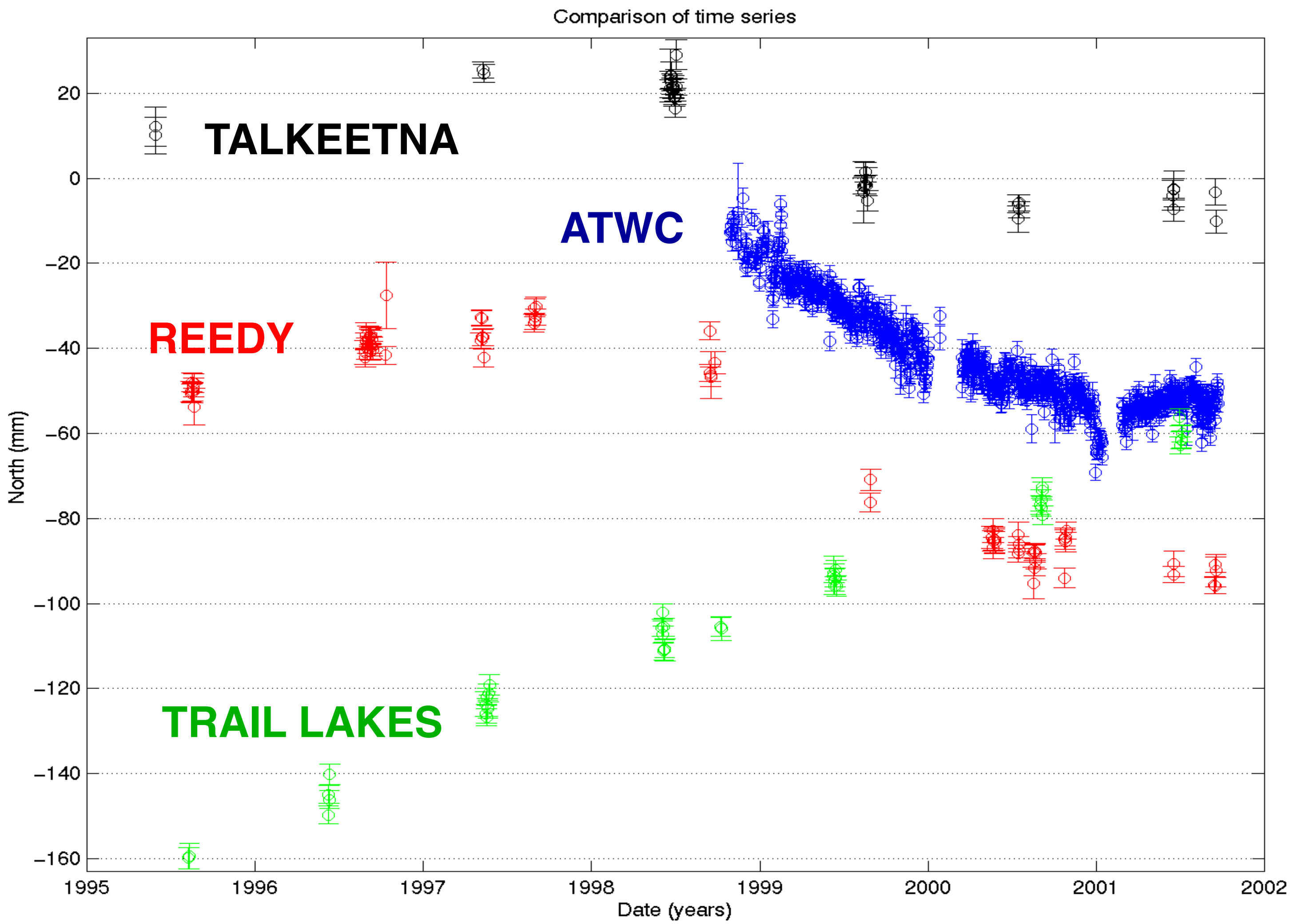


Suito and Freymueller (2009)

1993-1997 and 1997-2000 velocities relative to NOAM



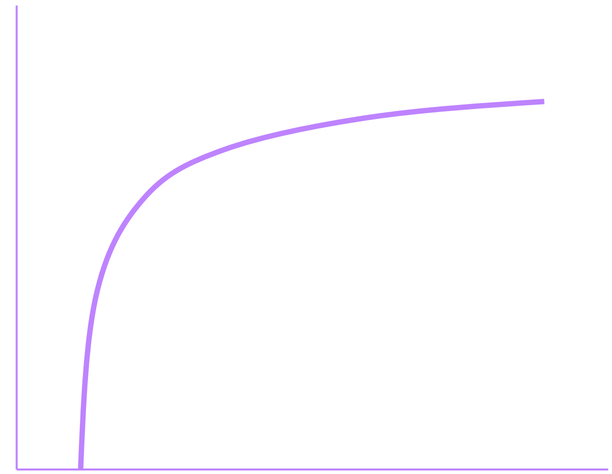
Comparison of Time Series



Afterslip Model for Time Series

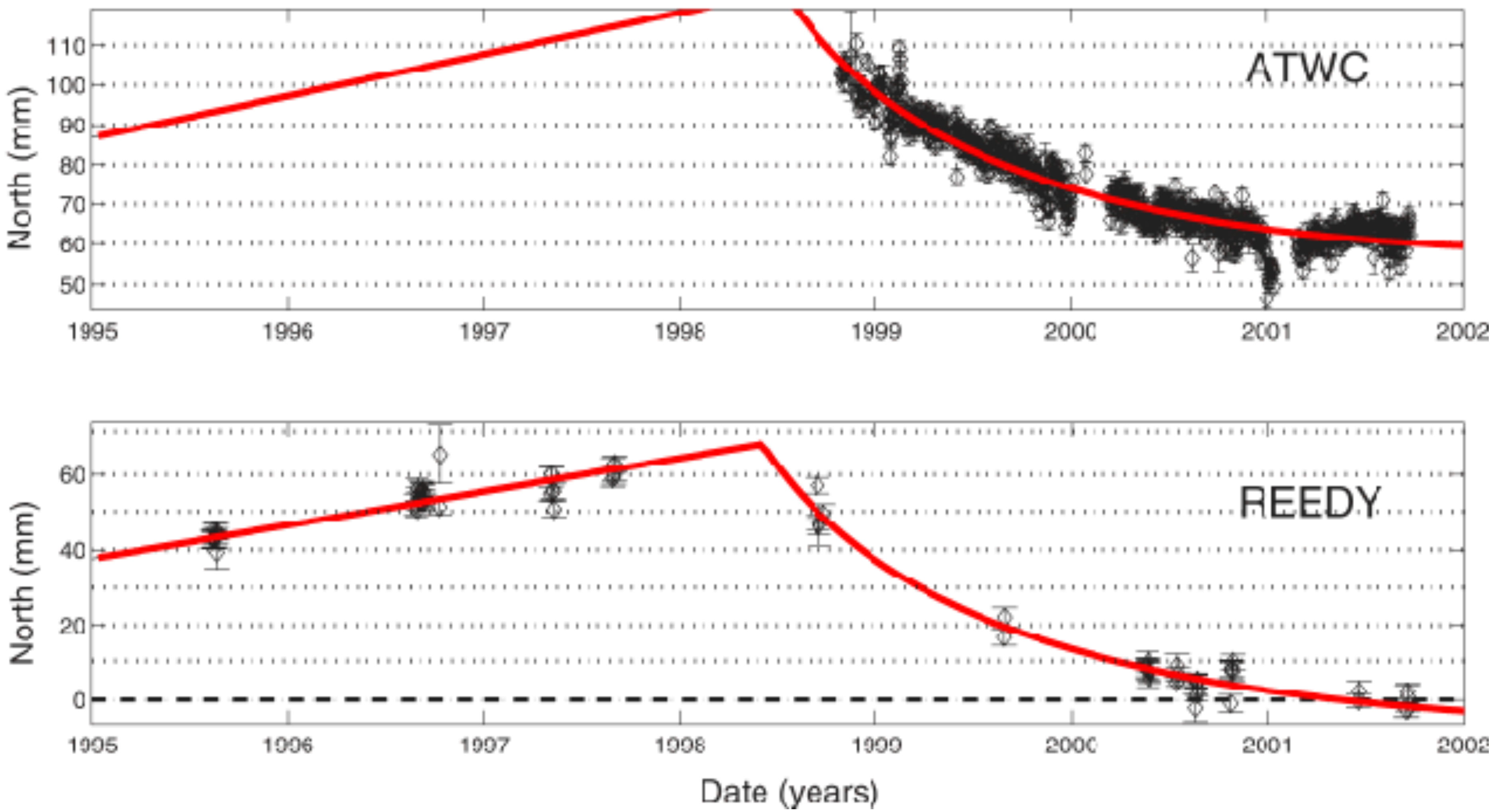
Non-linear inversion to fit each time series

- $n(t) = \boldsymbol{a} + \boldsymbol{b}t + \boldsymbol{c}\log(1+(t-\boldsymbol{t_0})/\boldsymbol{\tau})$
- Logarithmic decay characteristic of afterslip (Marone et al., 1991)
  - Rate and state-dependent friction law
  - Velocity-strengthening
  - Subjected to sudden stress step

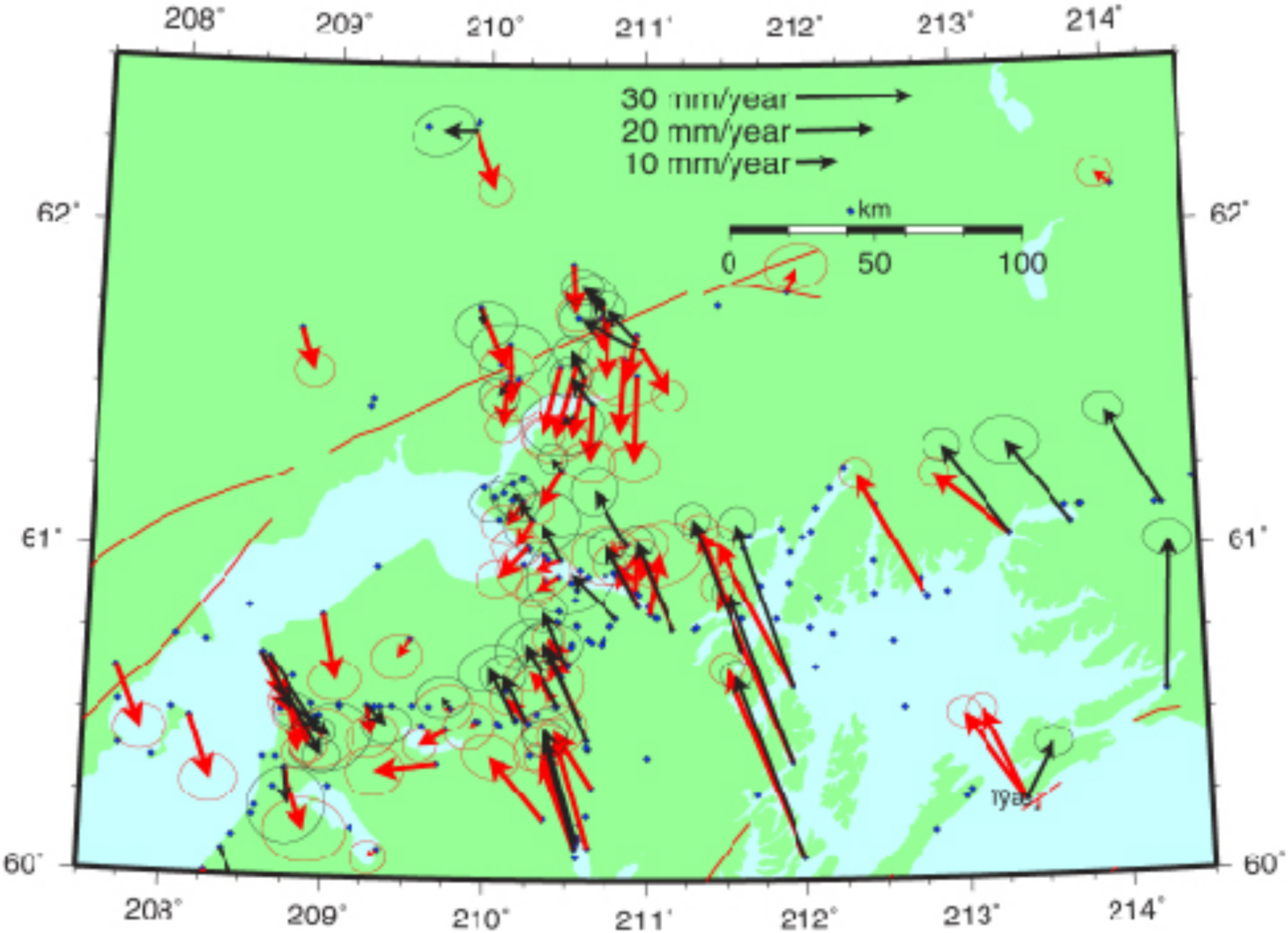


$\boldsymbol{t_0}$ = 1998.3 to 1998.6
τ = 0.3 to 0.6 years (120-220 days)
Hutton et al. (2001) found 100-150 days for Jalisco

Campaign vs. Continuous



1993-1997 and 1997-2000 velocities relative to NOAM



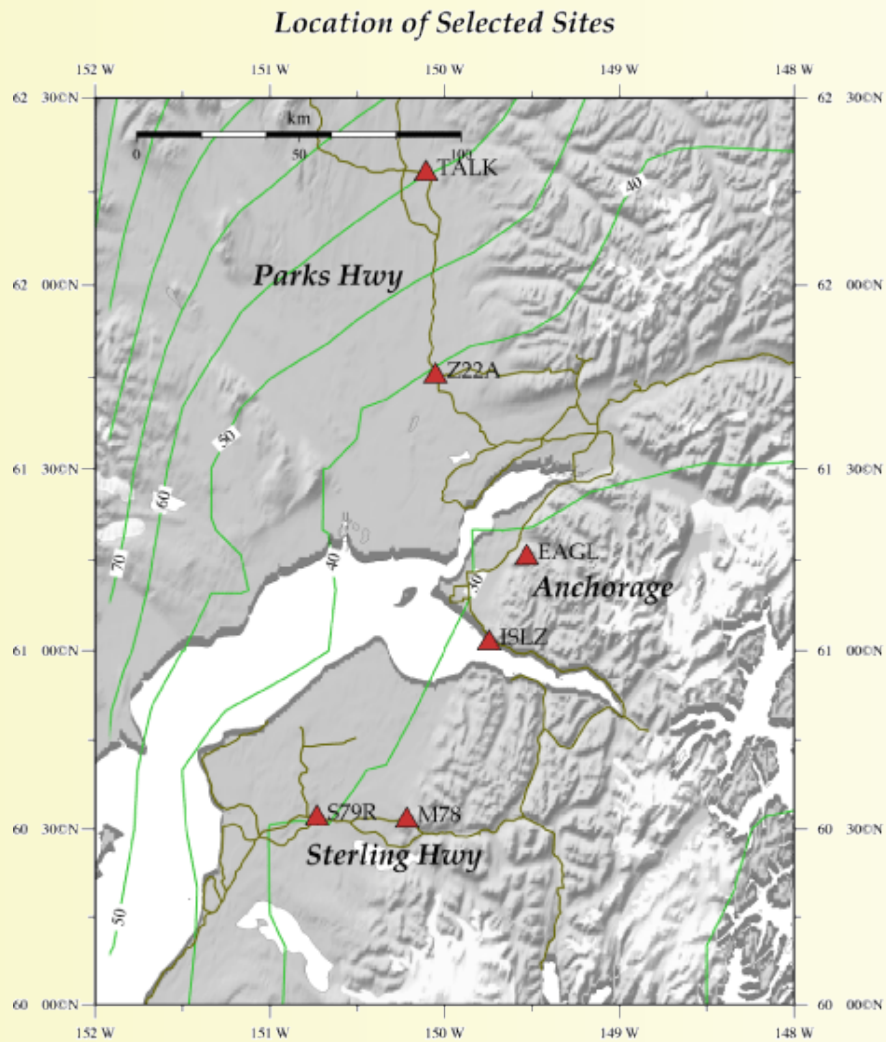
Summary of Observations

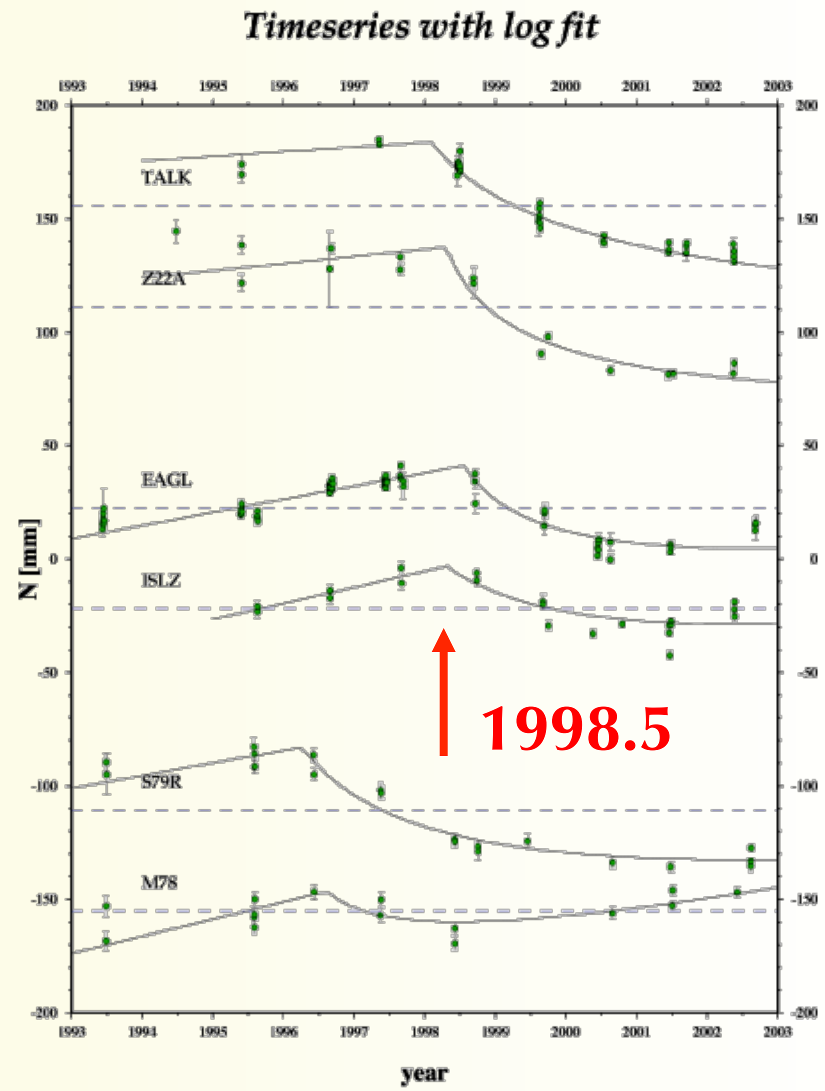
- Velocities over an area >15,000 km^2 changed dramatically at ~1998.5
- Large southward component, decaying with time
- Anomalous displacement ~log(1+t/0.6)
  - Functional form for afterslip in velocity-strengthening material obeying rate and state dependent friction law
- Preceded by decrease in seismicity rate within slab

Intepretations

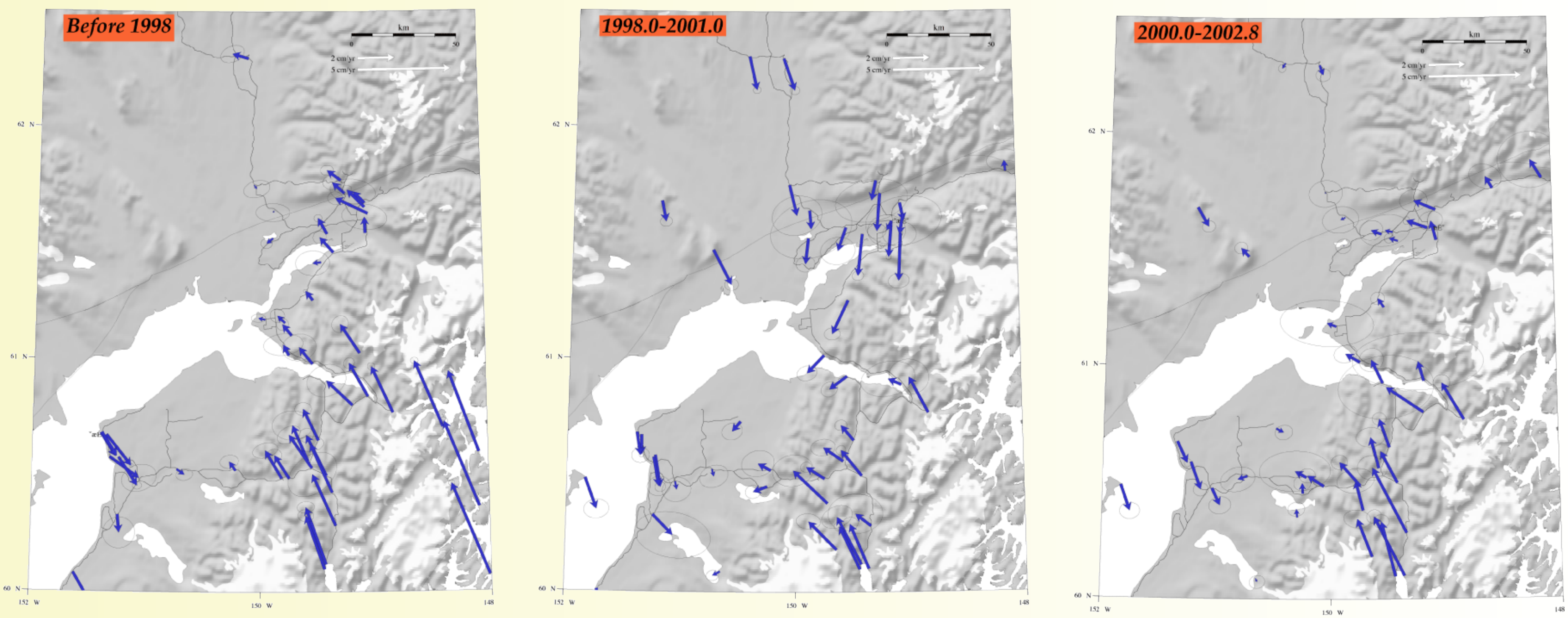
- Most compatible with a creep-type process on the plate interface downdip of seismogenic zone
  - NOT a transition from locked to creep, but from one rate of creep to a faster rate
- Trigger for event not clearly understood
  - NO significant (M > 5.5) earthquakes
  - NO apparent offset in time series = no sudden creep
- Possible link to continuing post-1964 slip transient
  - Did postseismic creep on adjacent segment trigger faster creep on this segment?
- Tide gauge observations at Anchorage suggest complex creep events have occurred in the past

Non-linear Deformation





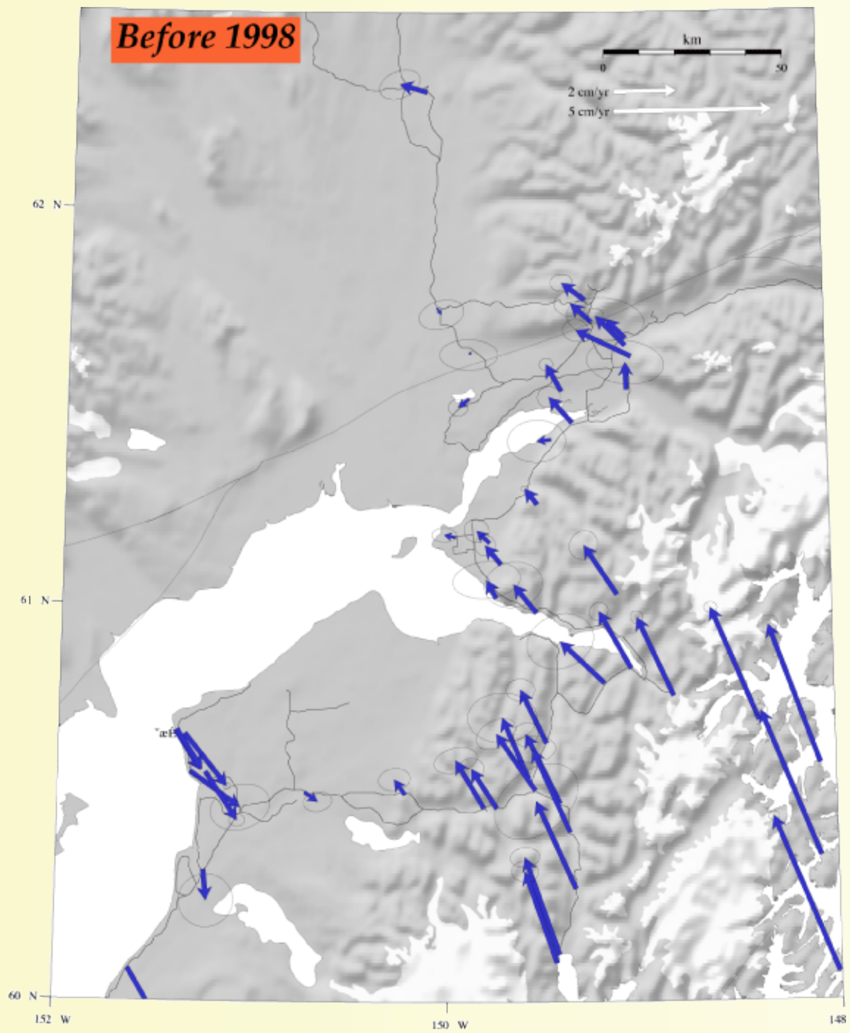
Three Time Periods

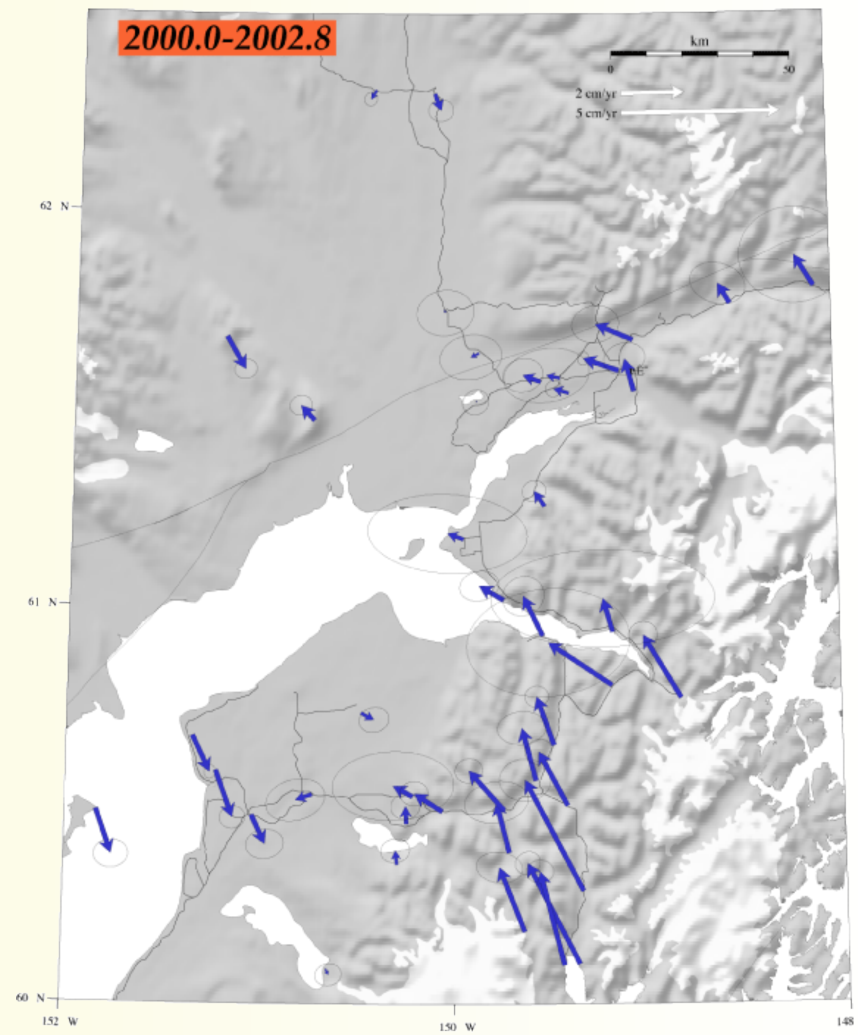


1998-2001

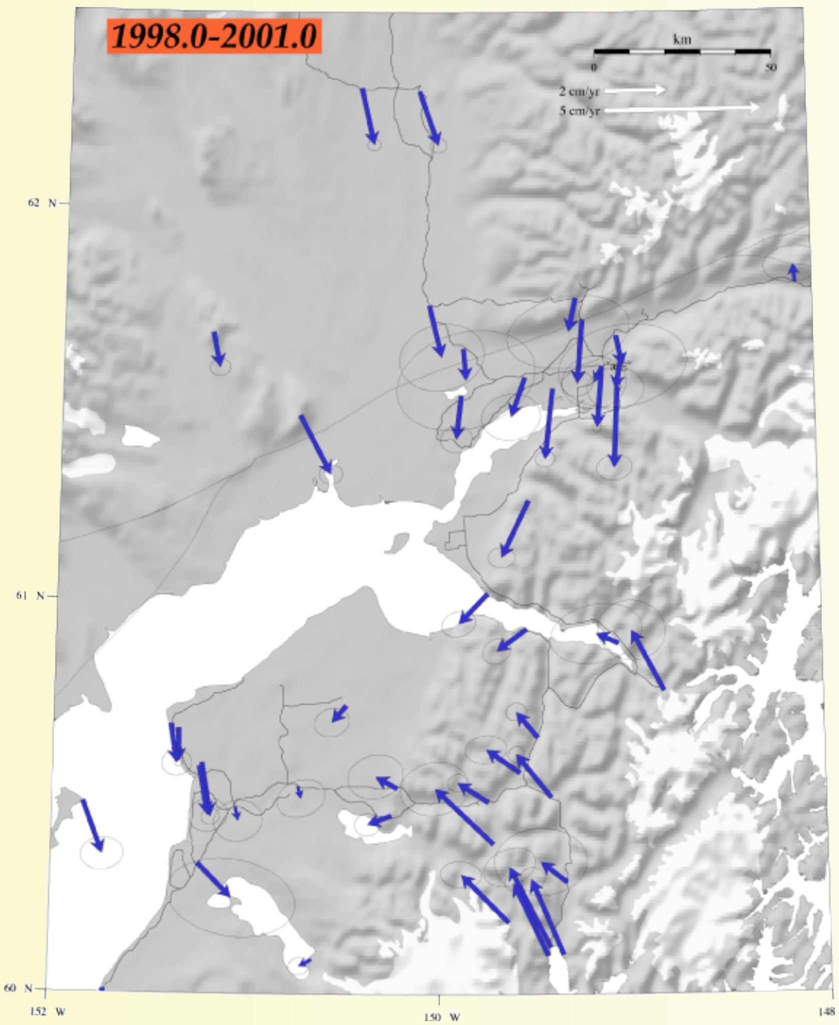
Velocities measurably different over area >100x200 km^2

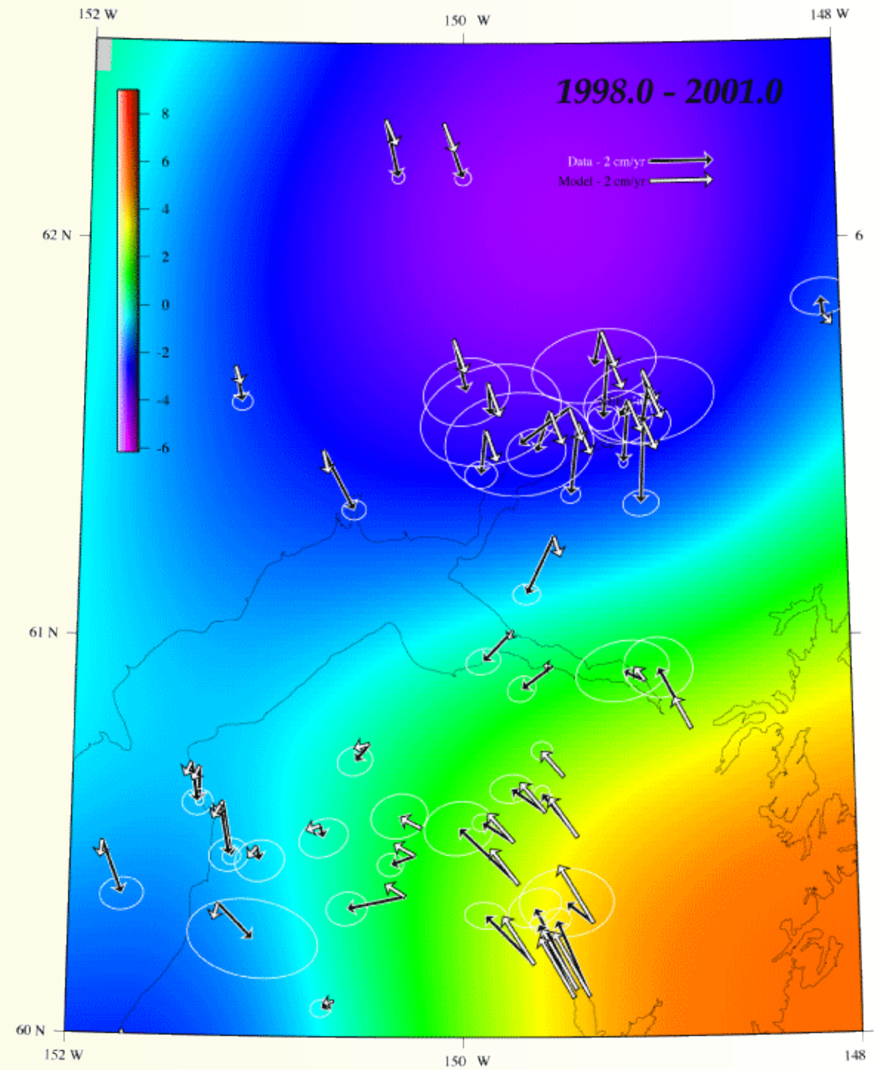
Before and After



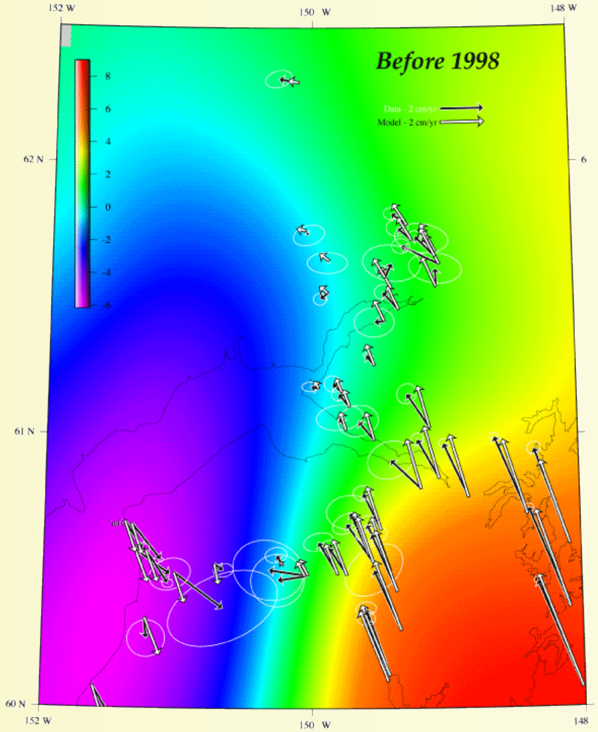


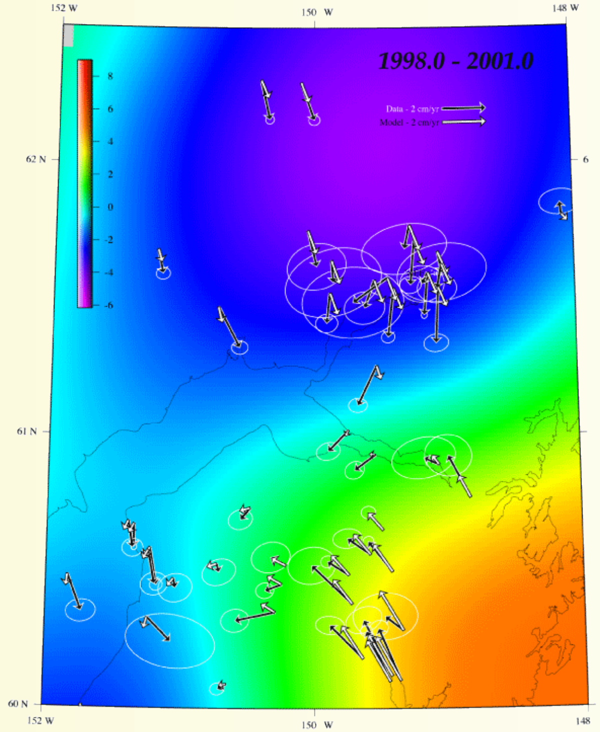
Data and Model

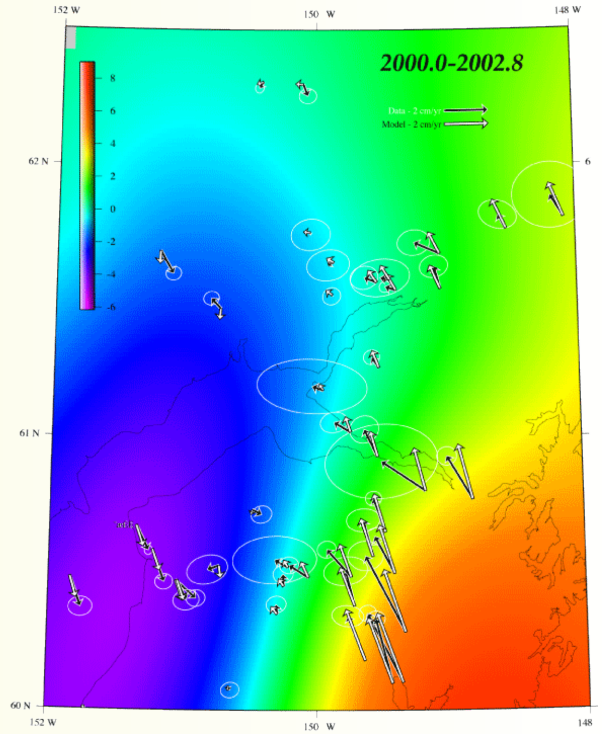




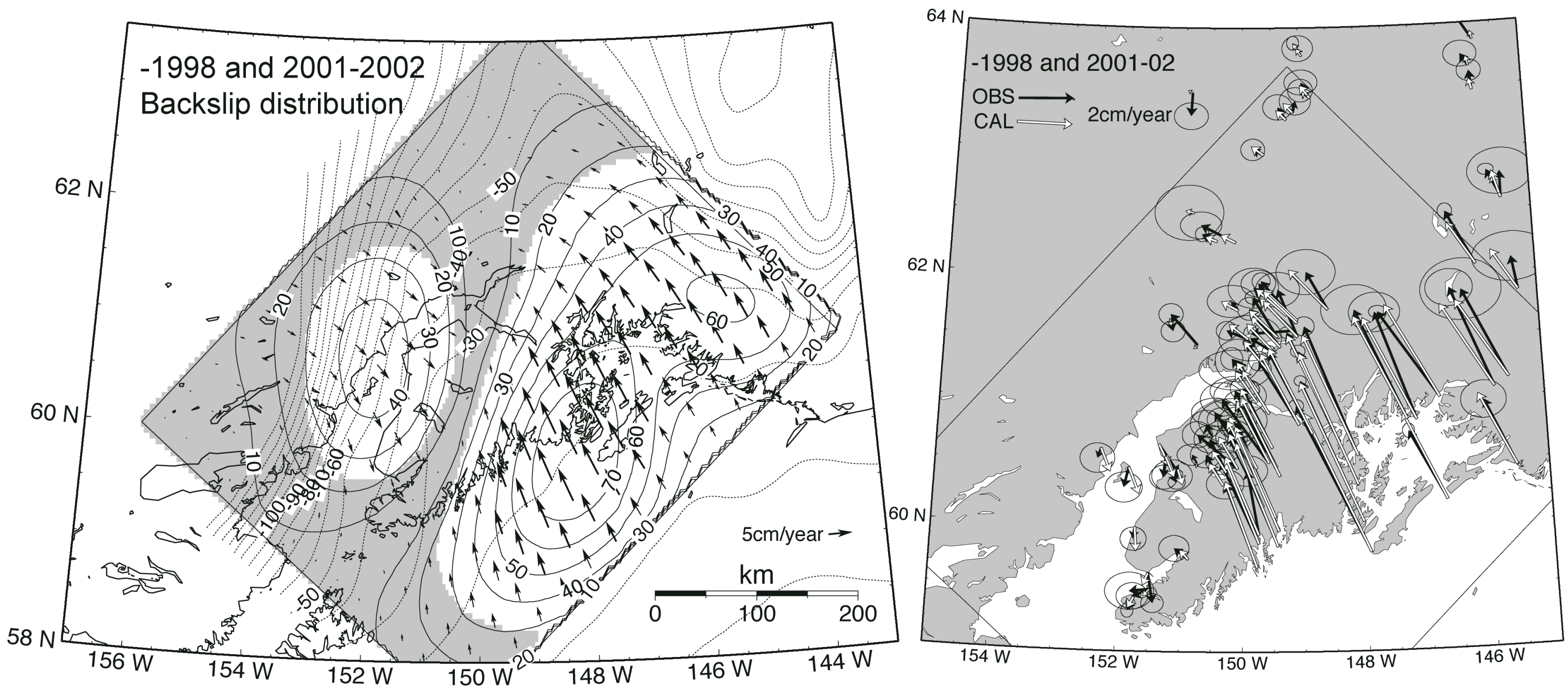
Comparison of Slip Models





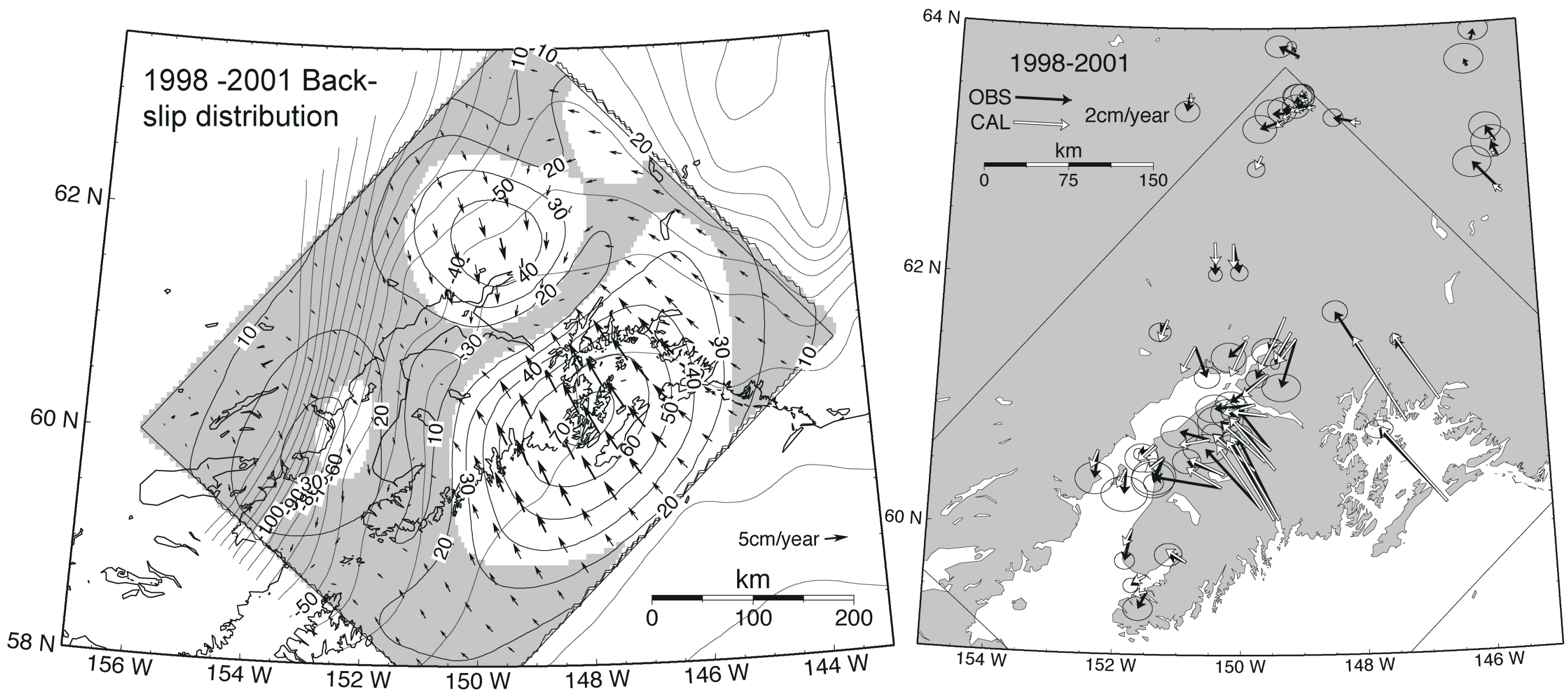


Slip Models through Time



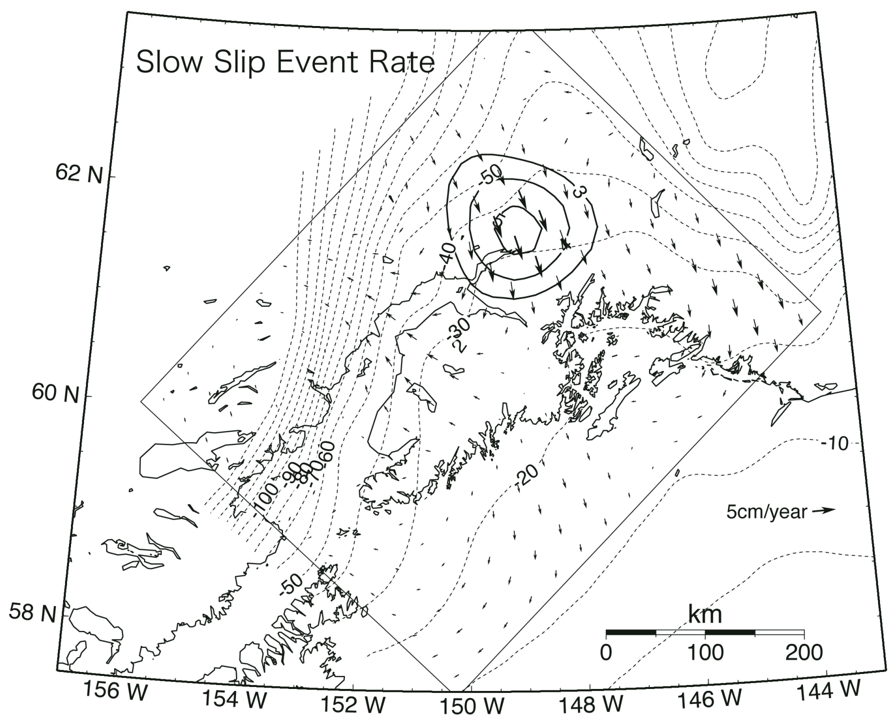
Ohta et al. (2006)

Slip Models through Time



Ohta et al. (2006)

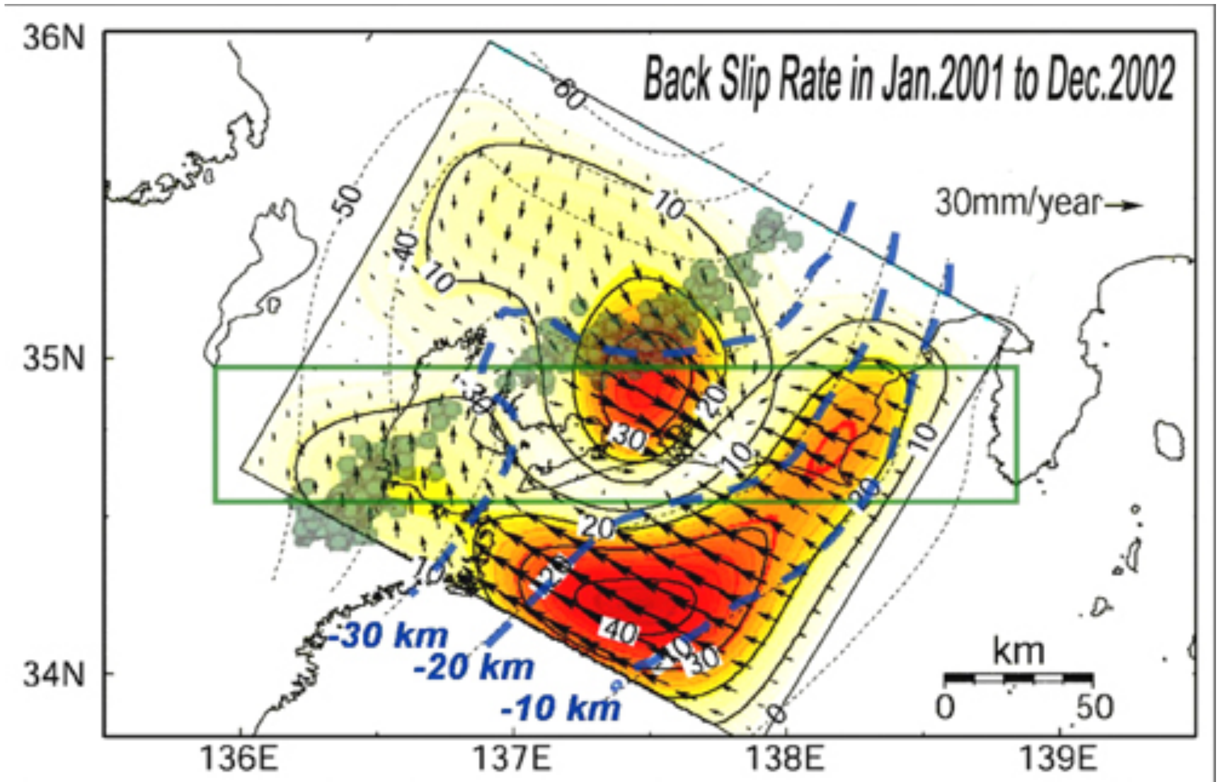
Slip Models through Time

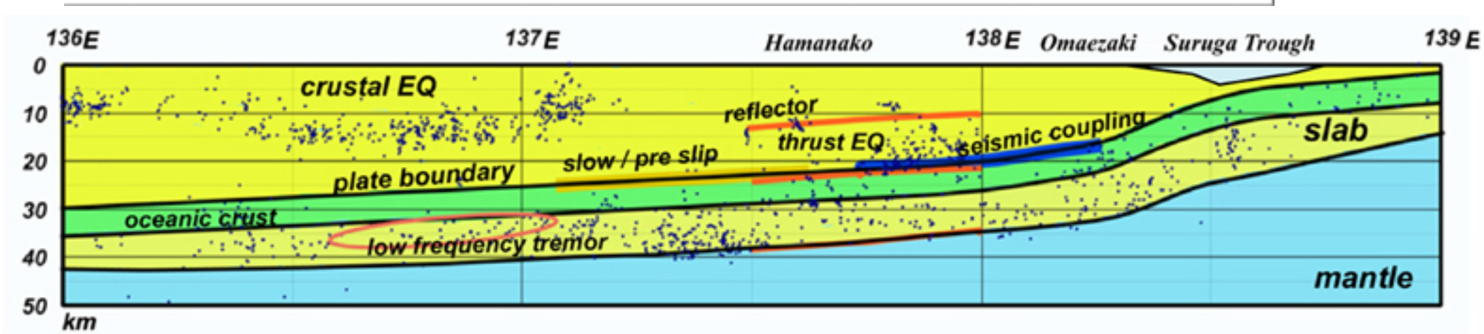


Ohta et al. (2006)

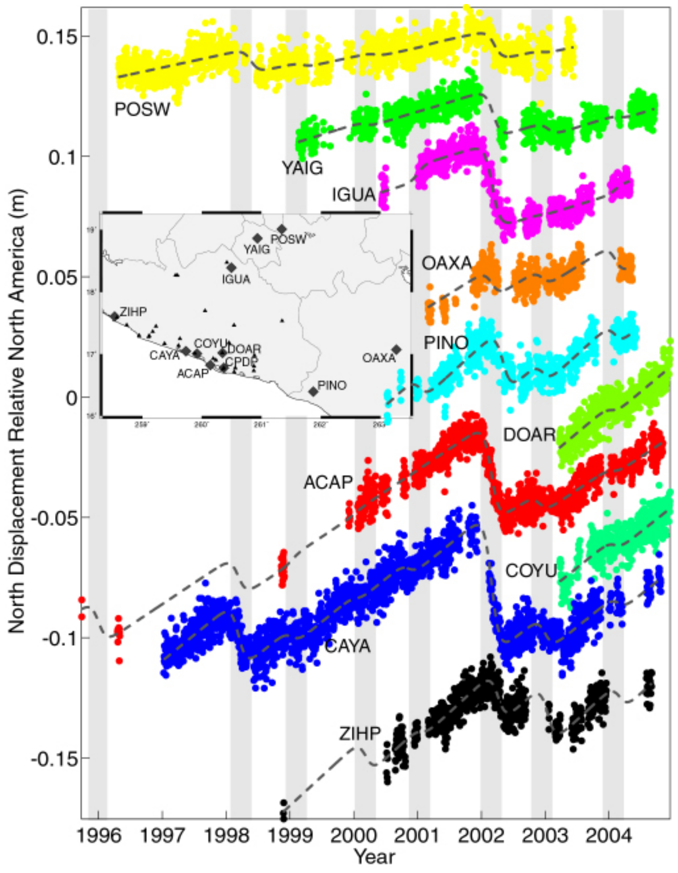
- The only difference between the two time periods is accelerated slip in one patch during SSE
- Located downdip of 1964 earthquake rupture
- Also associated with seismic tremor.

Tokai Slow Slip Event





Guerrero Slow Slip Events

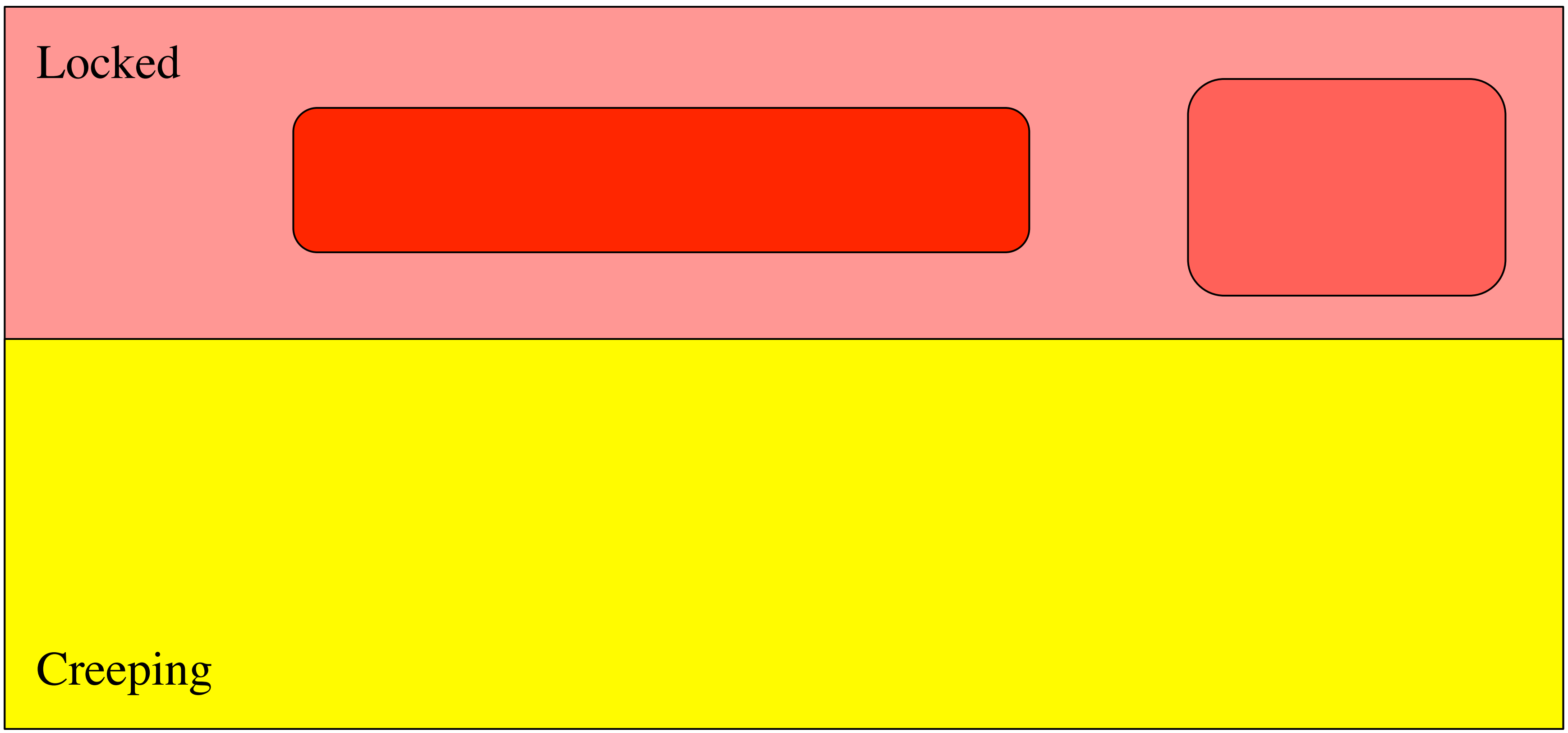


- From Kristine Larson
- Wide variety of events from Guerrero, Mexico
- Variety of spatial scales, durations, magnitudes
- Some events propagated along strike for a considerable distance.

Introduction to Stress Transfer

How does slip change stresses in surrounding area?

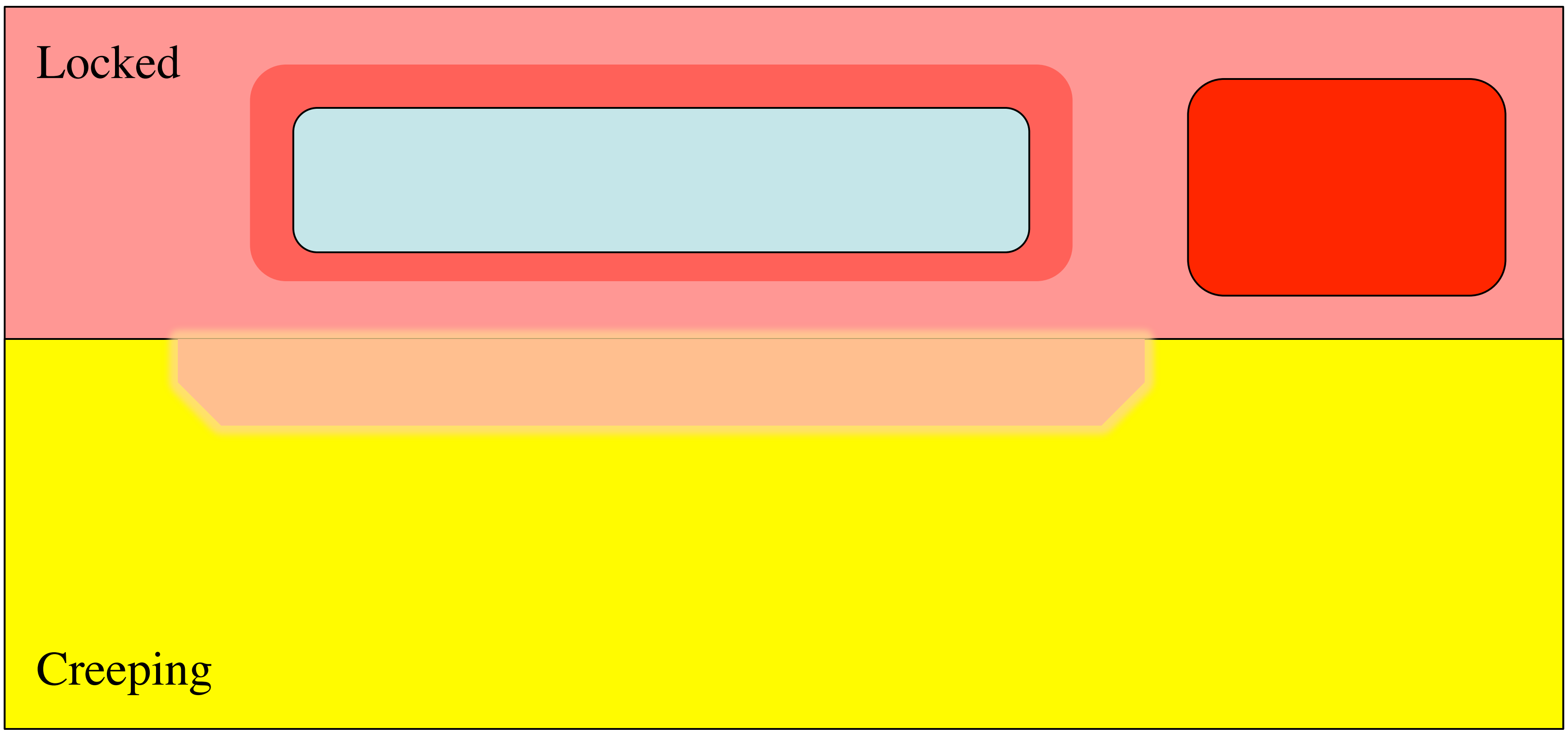
BEFORE



Introduction to Stress Transfer

How does slip change stresses in surrounding area?

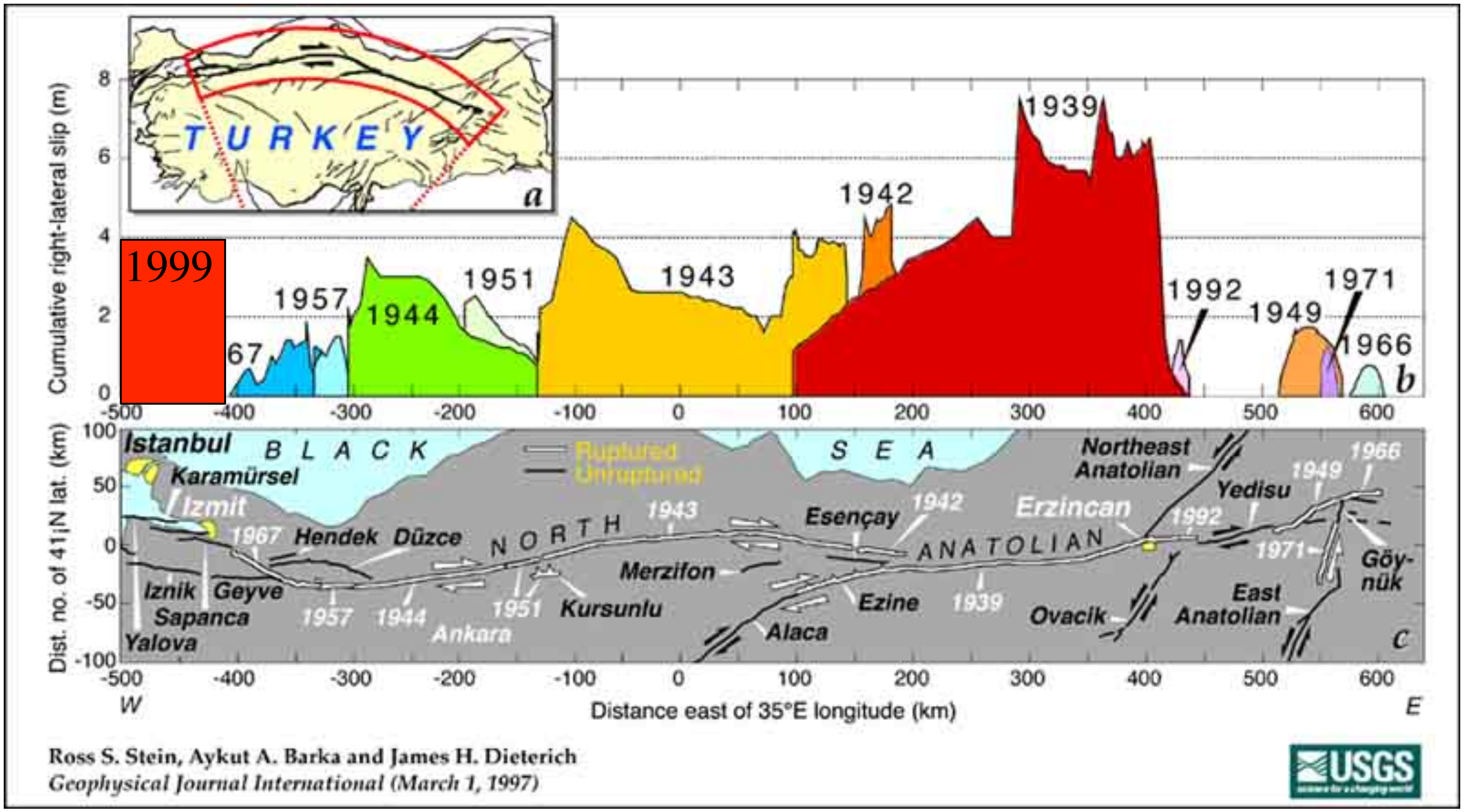
AFTER



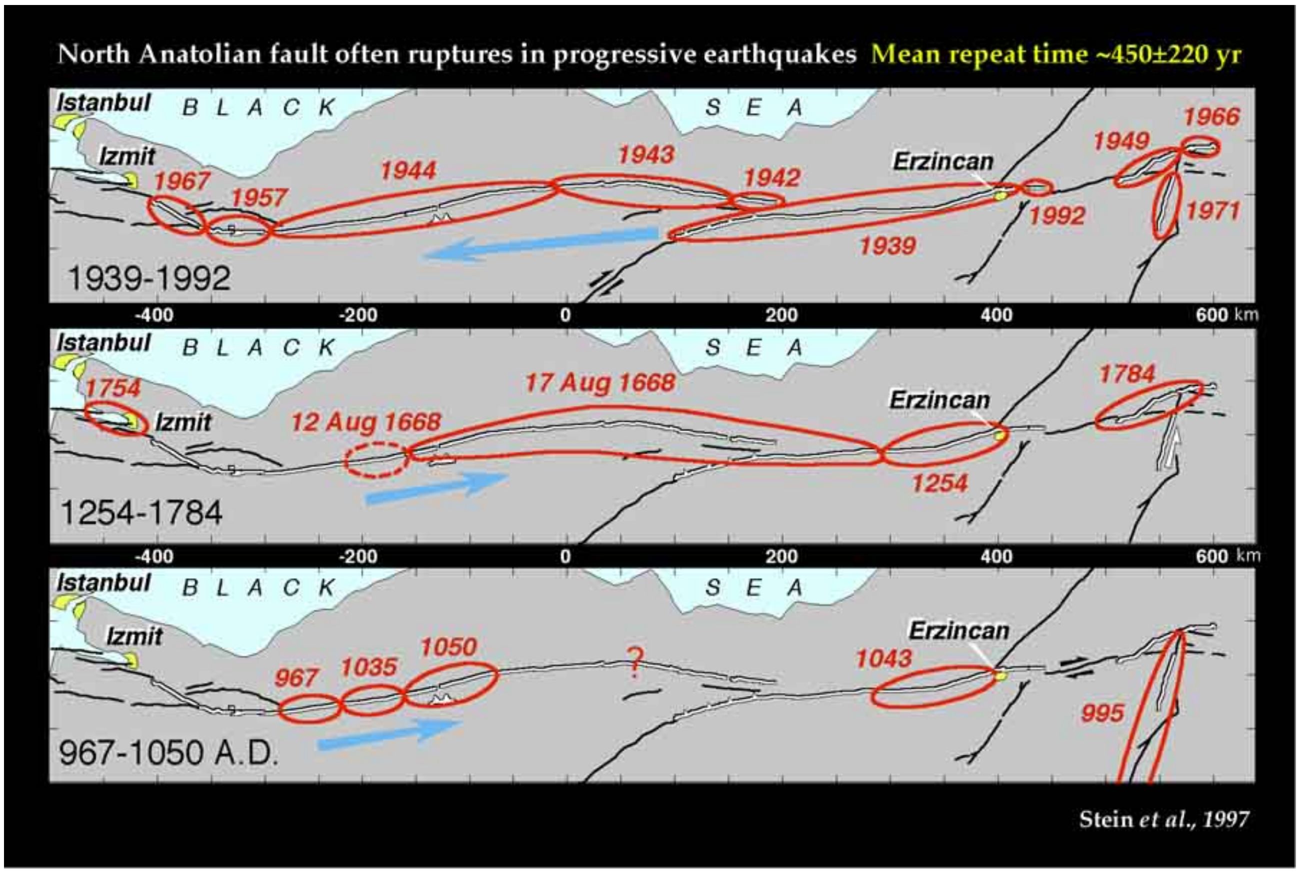
Effect of Slip

- Slip reduces shear stress in region that slipped, increases shear stress in surrounding region
- Slip may also change normal stresses.
- Postseismic deformation also changes stresses.
- Stress changes from one earthquake may bring another part of the fault or another fault closer to failure – triggering.

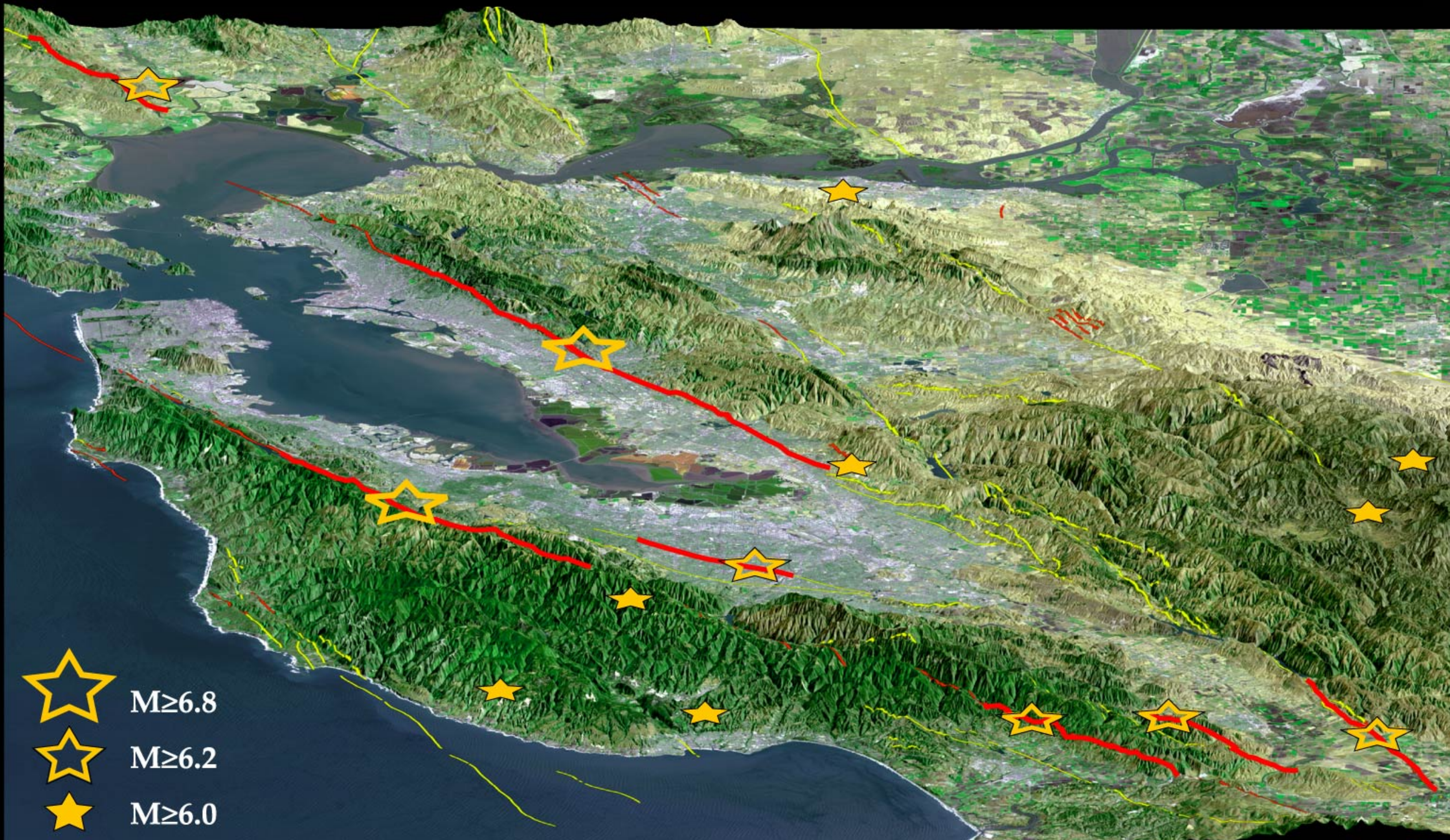
Stress Transfer, or "Conversations between Earthquakes"



Sequence Has Repeated

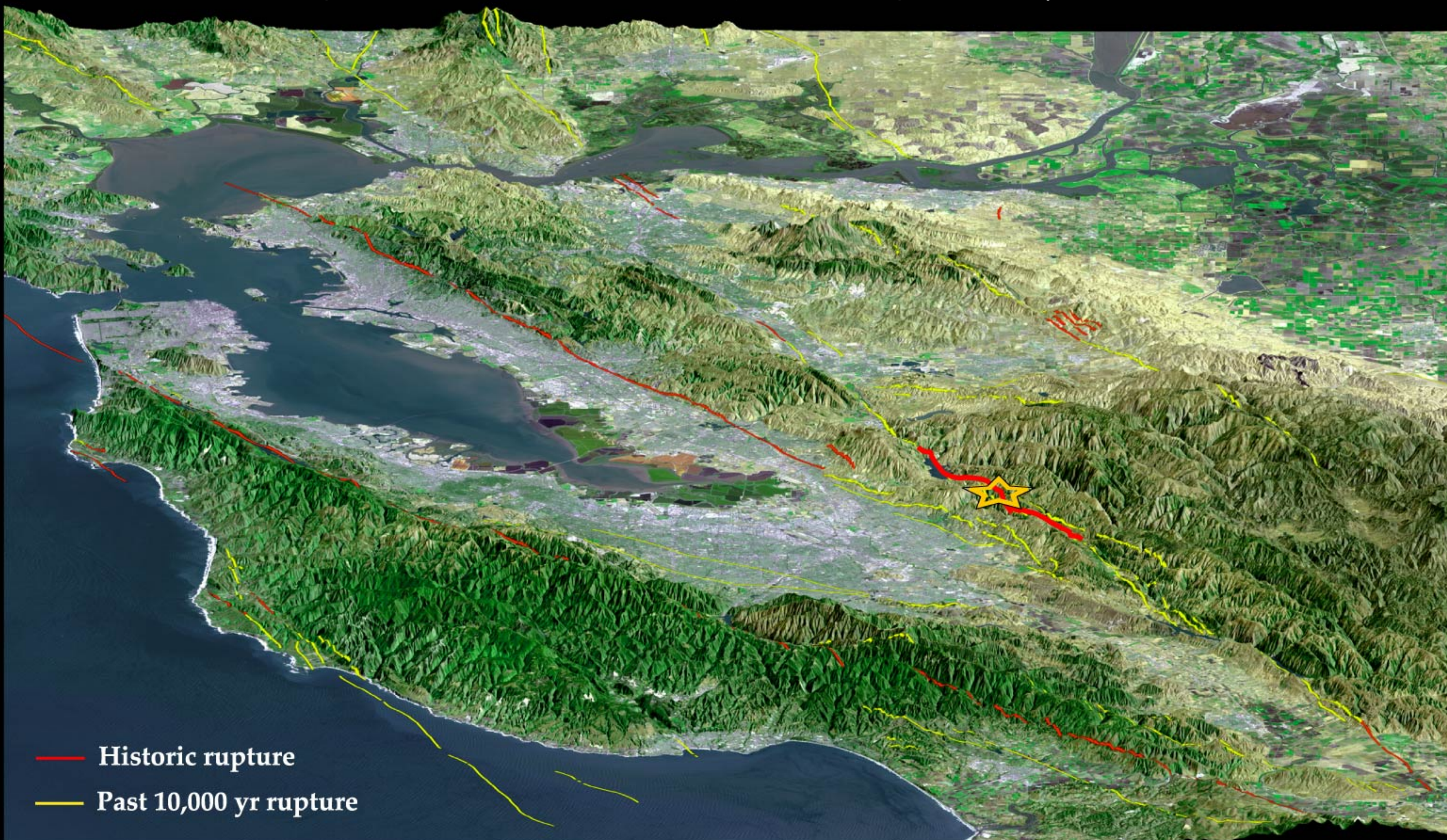


Bay area shocks during the 75 years *before* 1906

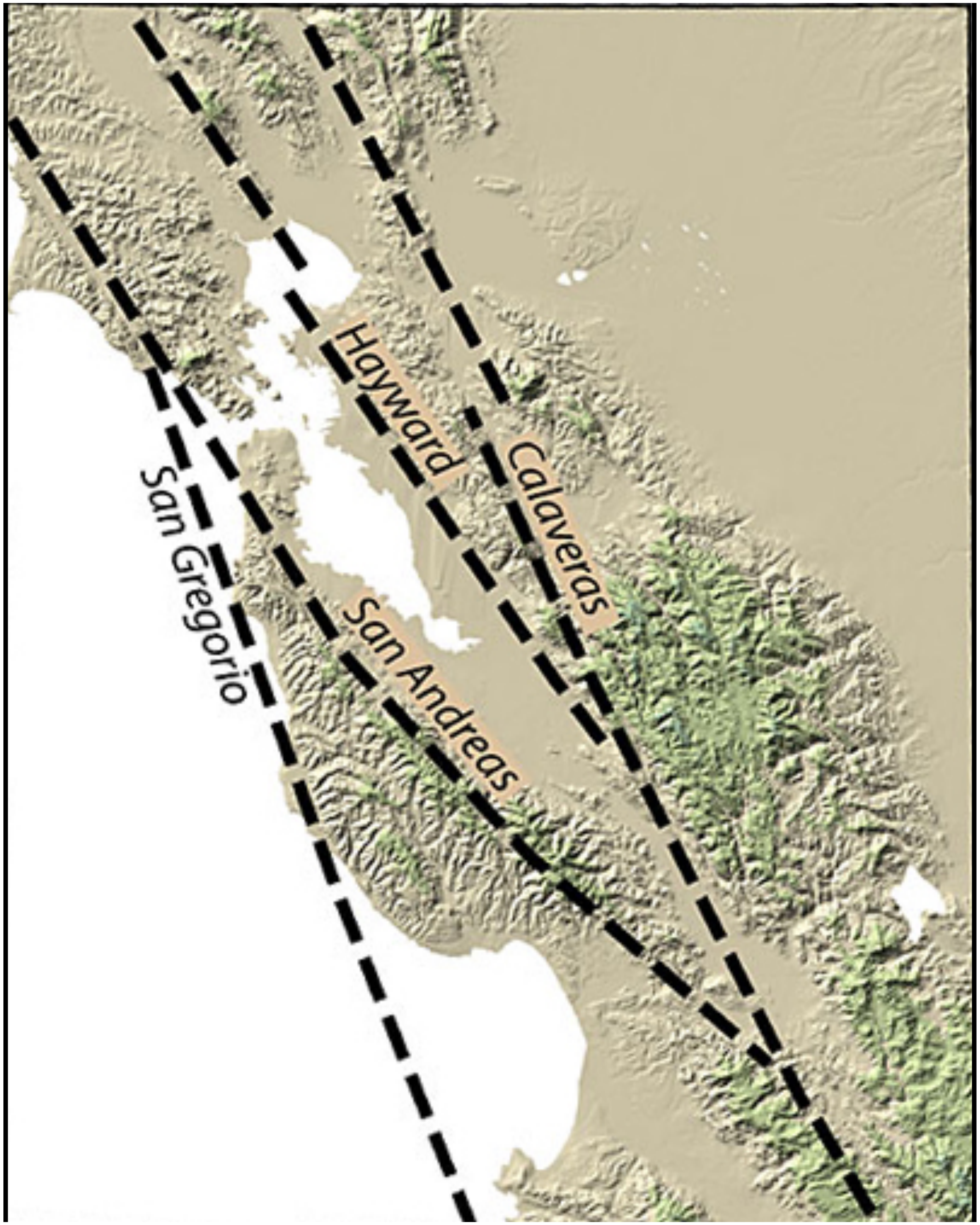


Earthquakes from *Bakun* [1999] and *Ellsworth* [1990]

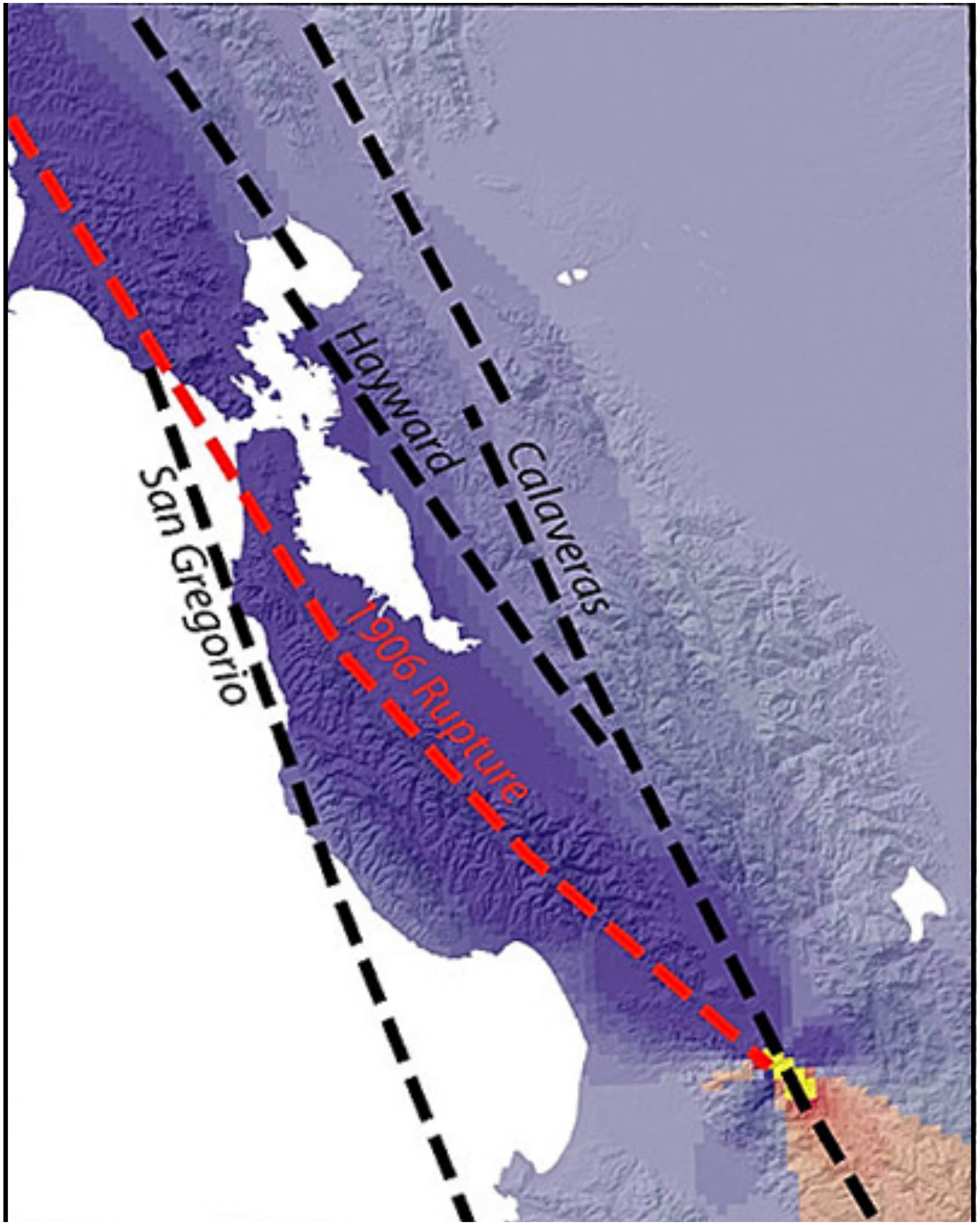
Bay area shocks during the 75 years *after* 1906



1911 M=6.2 shock from *Bakun* [BSSA, 1999]



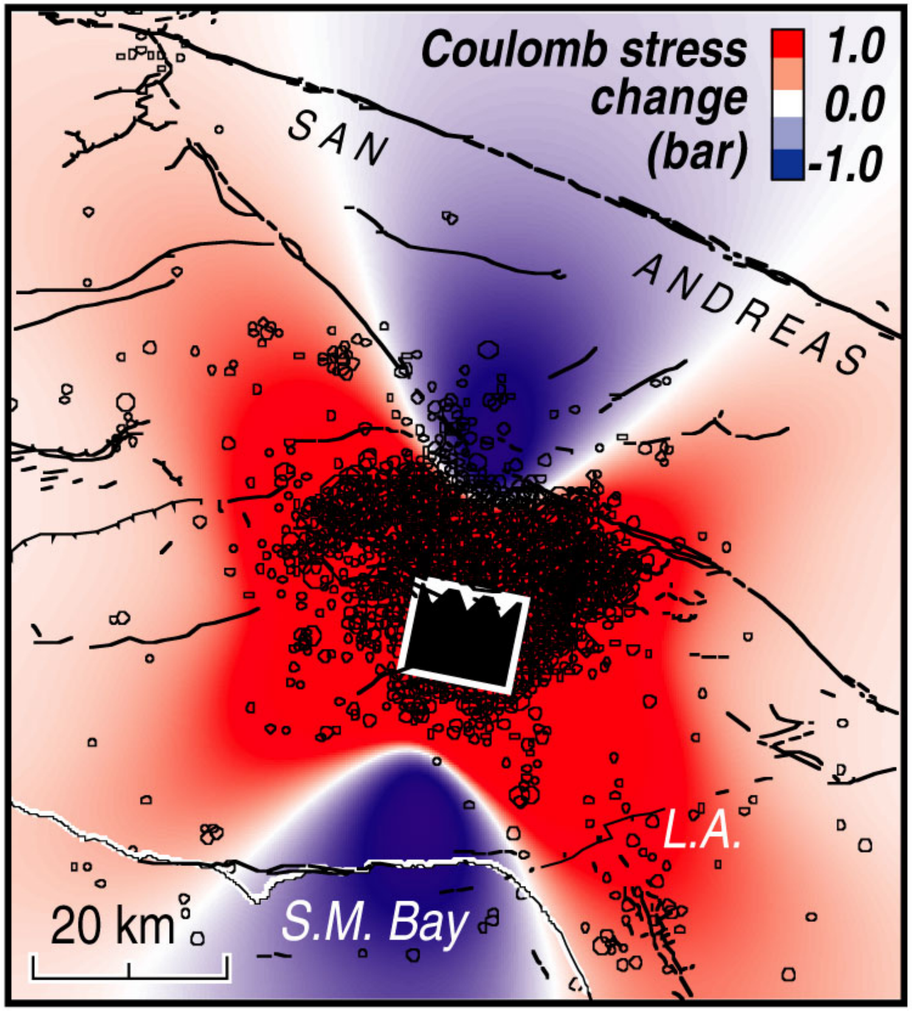
Bay area is a system of roughly parallel faults



Bay area faults may have fallen under a stress shadow in 1906

from *Harris & Simpson* (1998) and *Parsons* (2003)

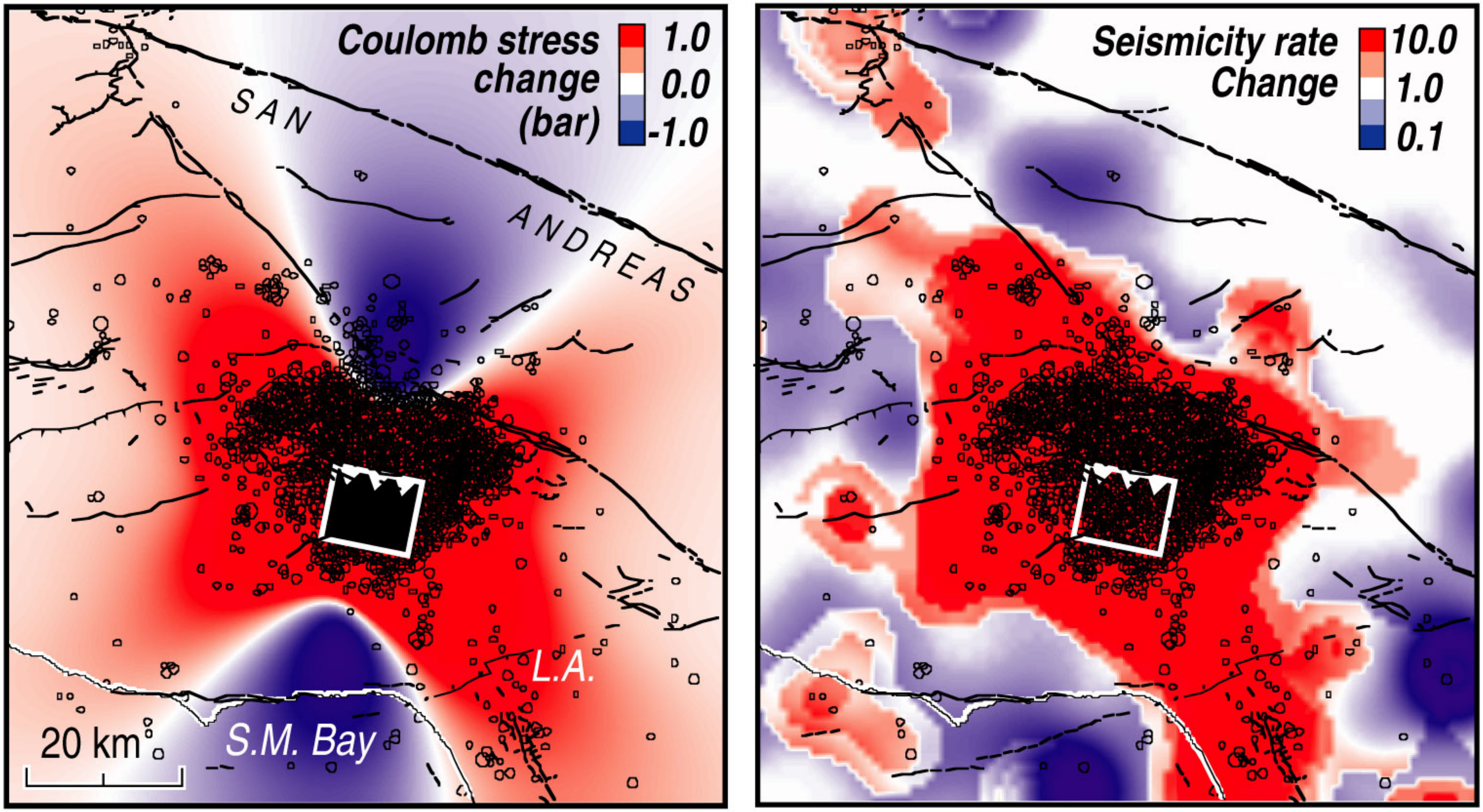
Stress change is correlated with seismicity rate change for 1994 M=6.7 Northridge shock



M≥1.5 shocks 3-6 months after mainshock plotted

from *Stein* (***Nature***, 1999)

Stress change is correlated with seismicity rate change for 1994 M=6.7 Northridge shock



from *Stein* (***Nature,*** 1999)

Coulomb Failure Criterion

- Slip on a fault will occur if the shear stress resolved on the fault plane exceeds the force of friction retarding slip:

$$\tau \geq \mu(\sigma - p)$$

- Define the Coulomb stress change as:

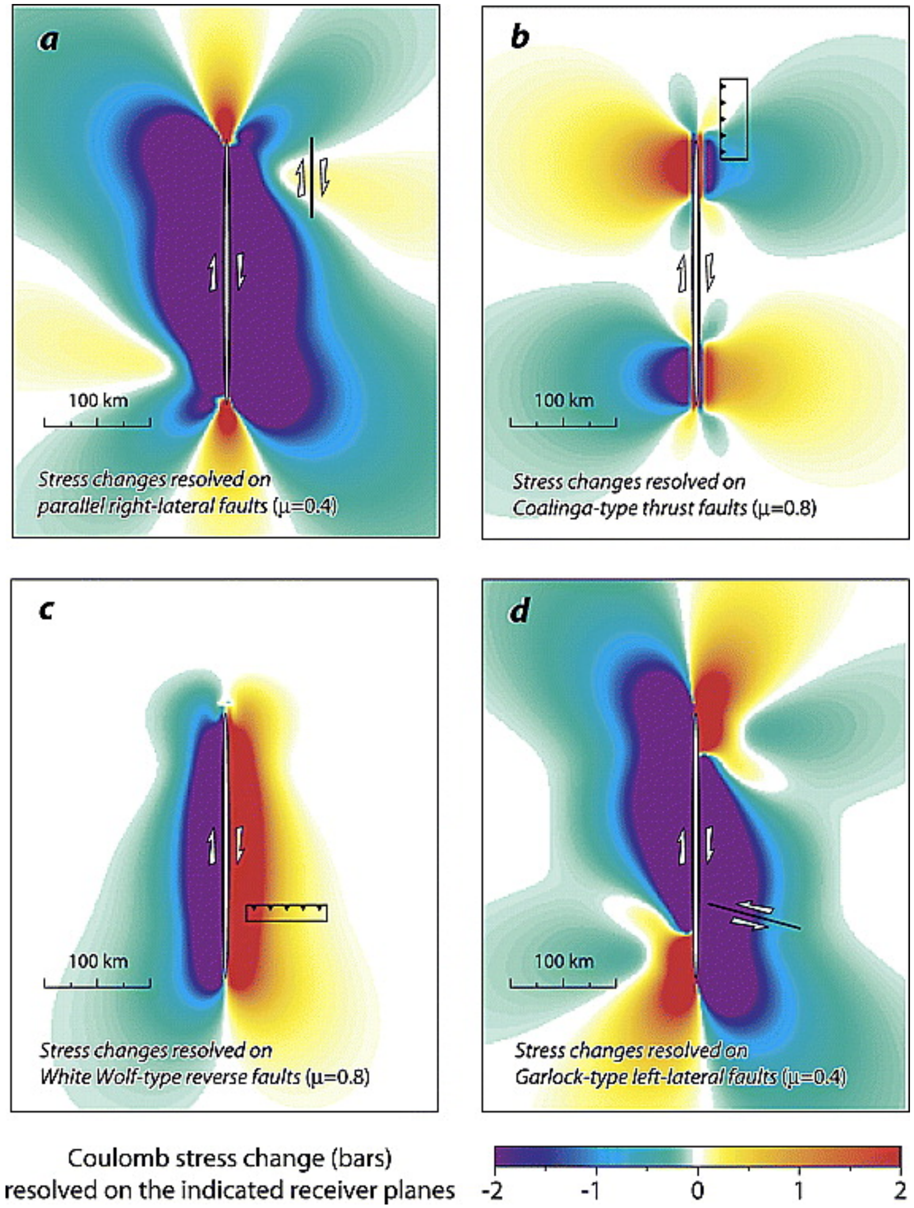
$$\Delta CFS = \Delta\tau - \mu\Delta(\sigma - p)$$

$$\Delta CFS = \Delta\tau - \mu'\Delta\sigma$$

How to Calculate

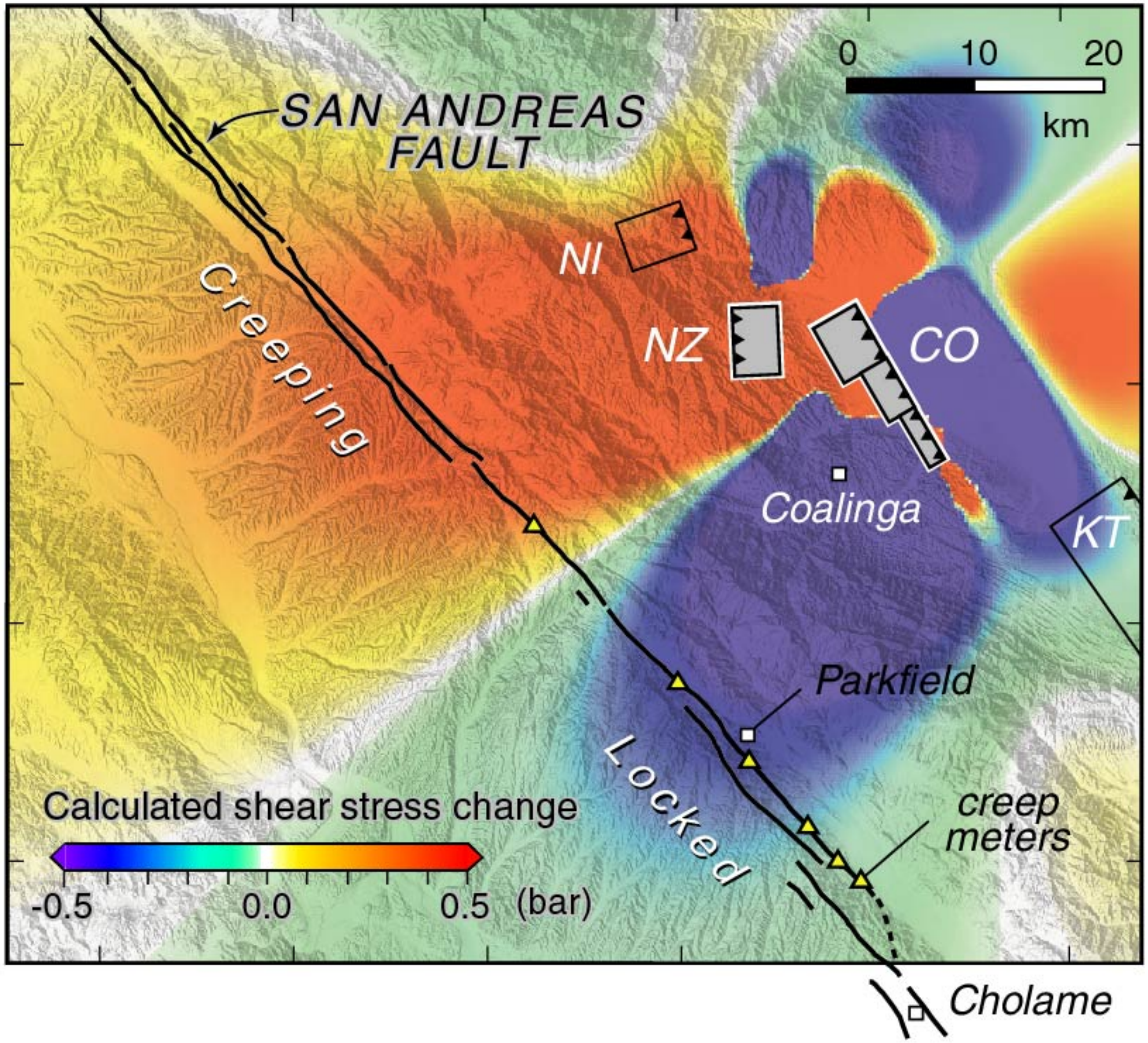
- Start with a model of source of deformation
  - Usually slip on a fault using Okada's formulation of dislocation theory
- Calculate strain tensor at desired points by calculating strain components at a depth of choice
- Convert strain tensor to change in stress tensor using linear elasticity
- Resolve delta-stress tensor onto desired fault plane(s) based on geometry of fault

Effect Depends on Orientation of "Receiver fault"



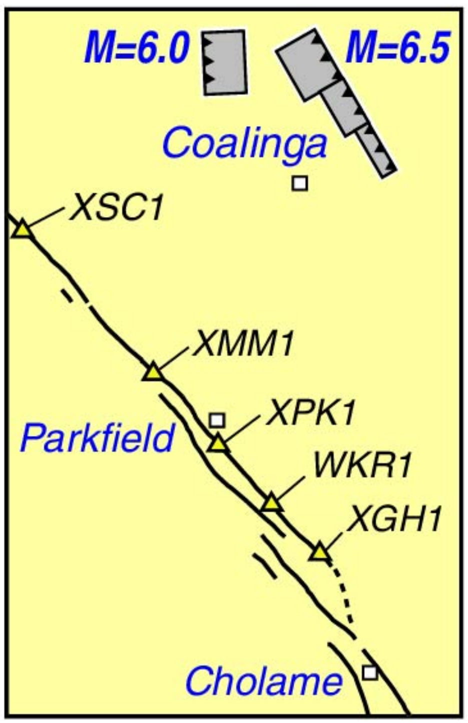
- Stress tensor changes depend on the "source fault"
- Coulomb stress also depends on the geometry of "receiver fault"
  - Fancy graphics for Coulomb stress change assume receiver fault
  - Specific fault or "optimally-oriented strike slip"

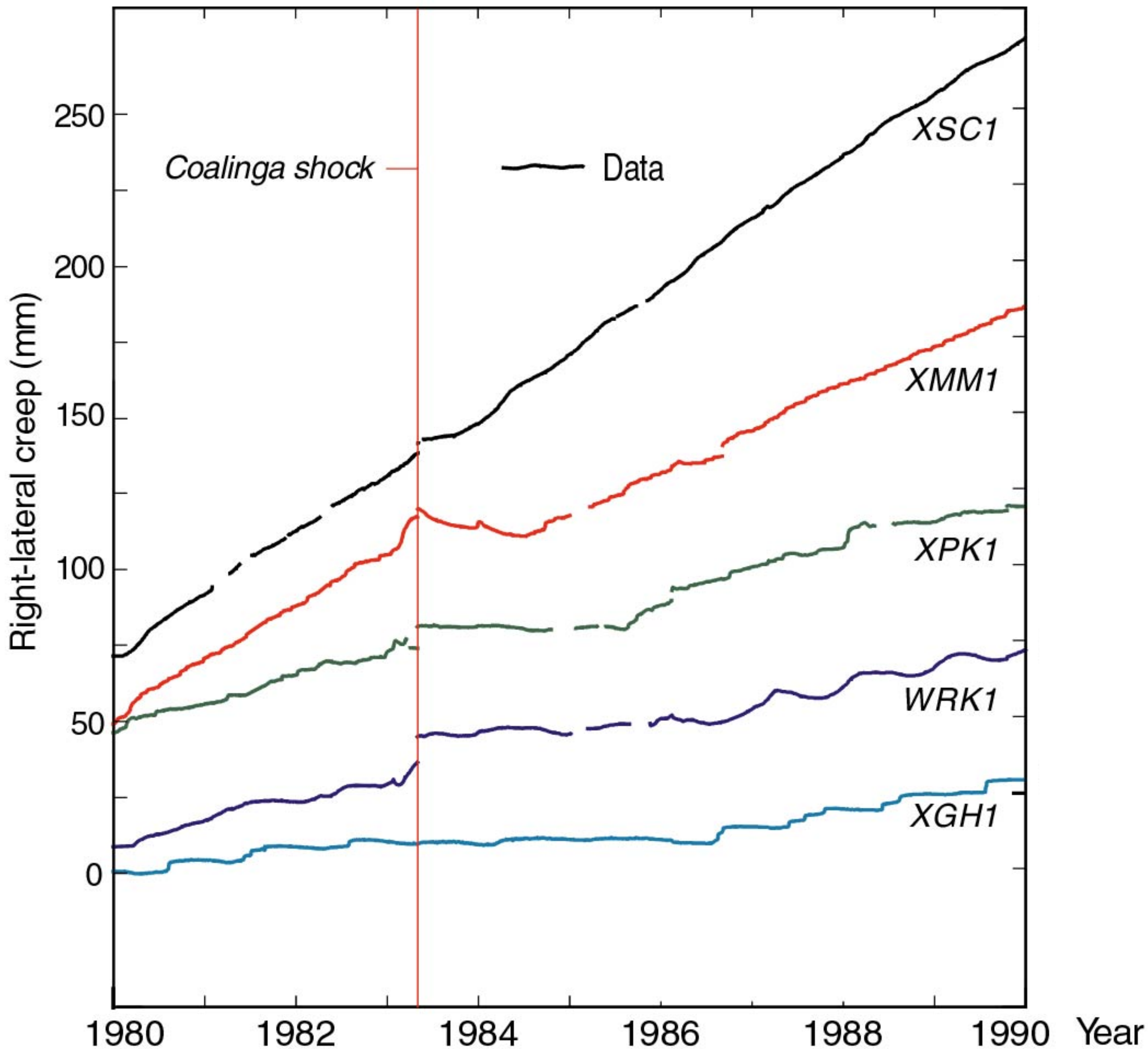
Calculated shear stress imposed by Coalinga on planes parallel to the San Andreas fault at 8 km depth



from *Toda & Stein* (JGR, 2003)

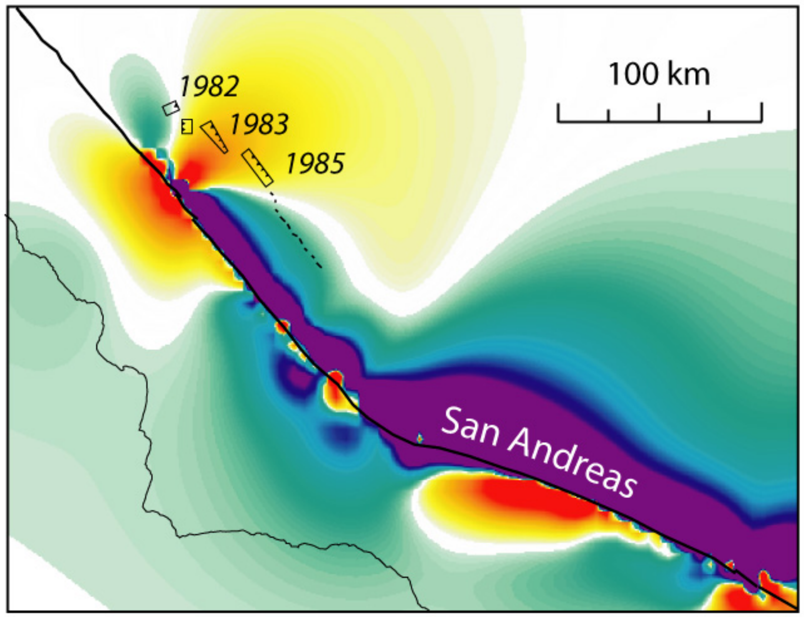
Fault creep was retarded or reversed by Coalinga earthquake



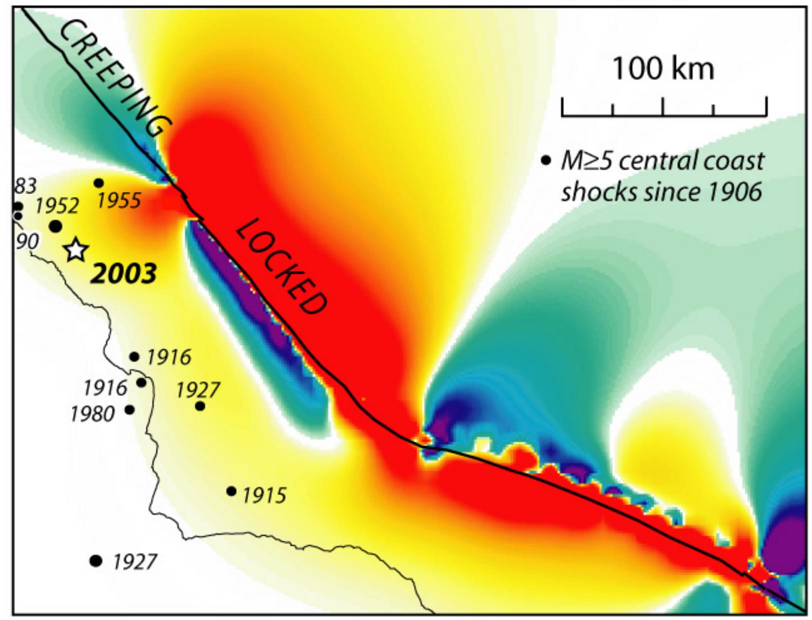


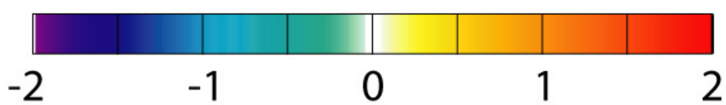
Stress accumulated *since* great 1857 shock loads Coast Ranges thrust faults

Interseismic stress accumulation, 1857-1983

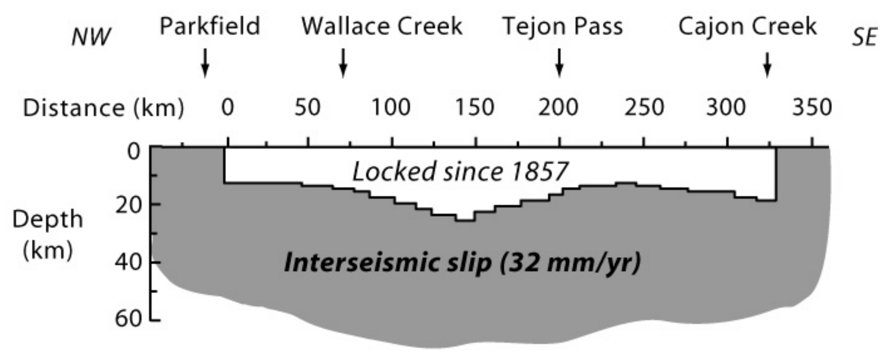


Interseismic stress accumulation, 1857-2003



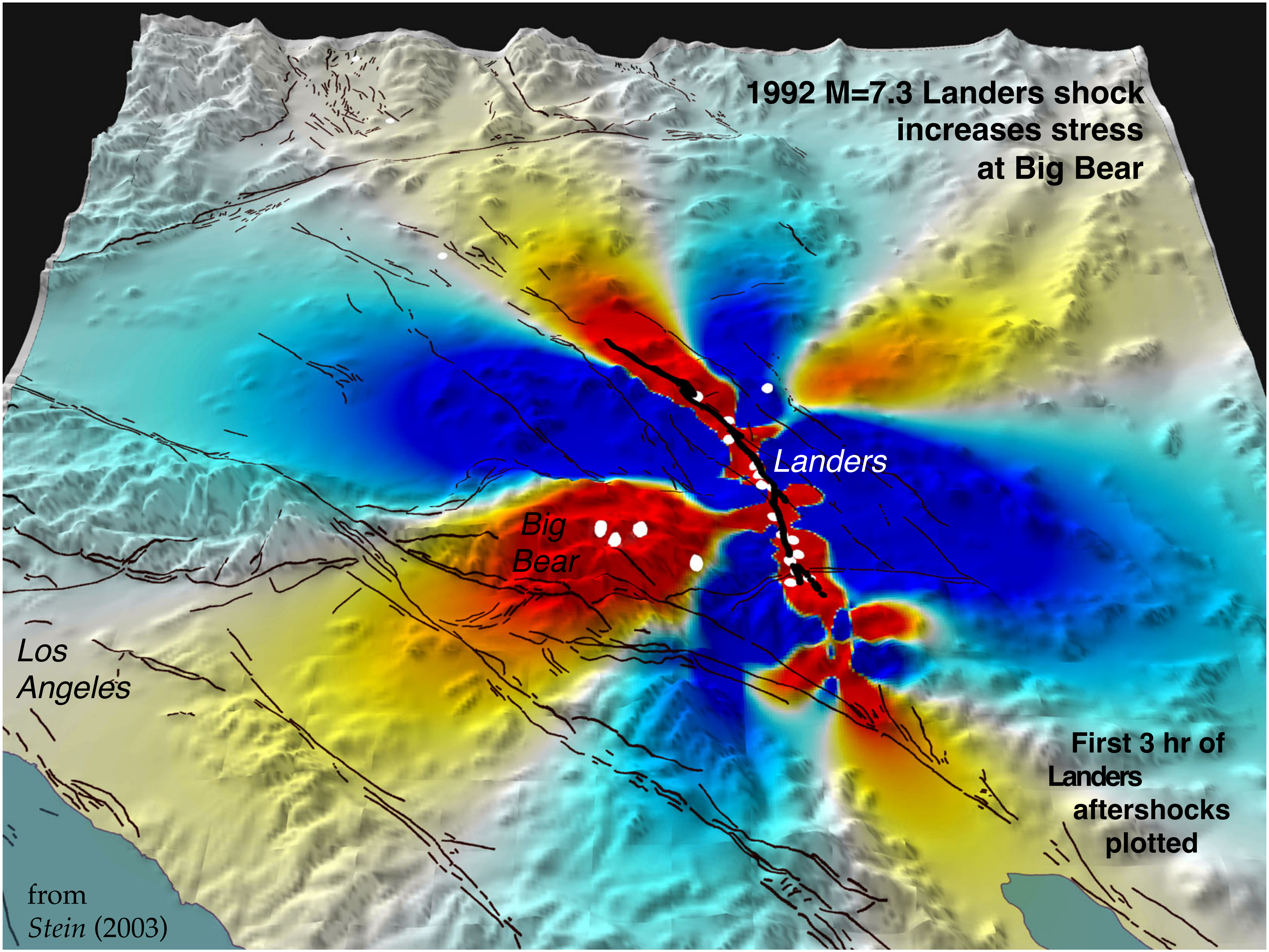


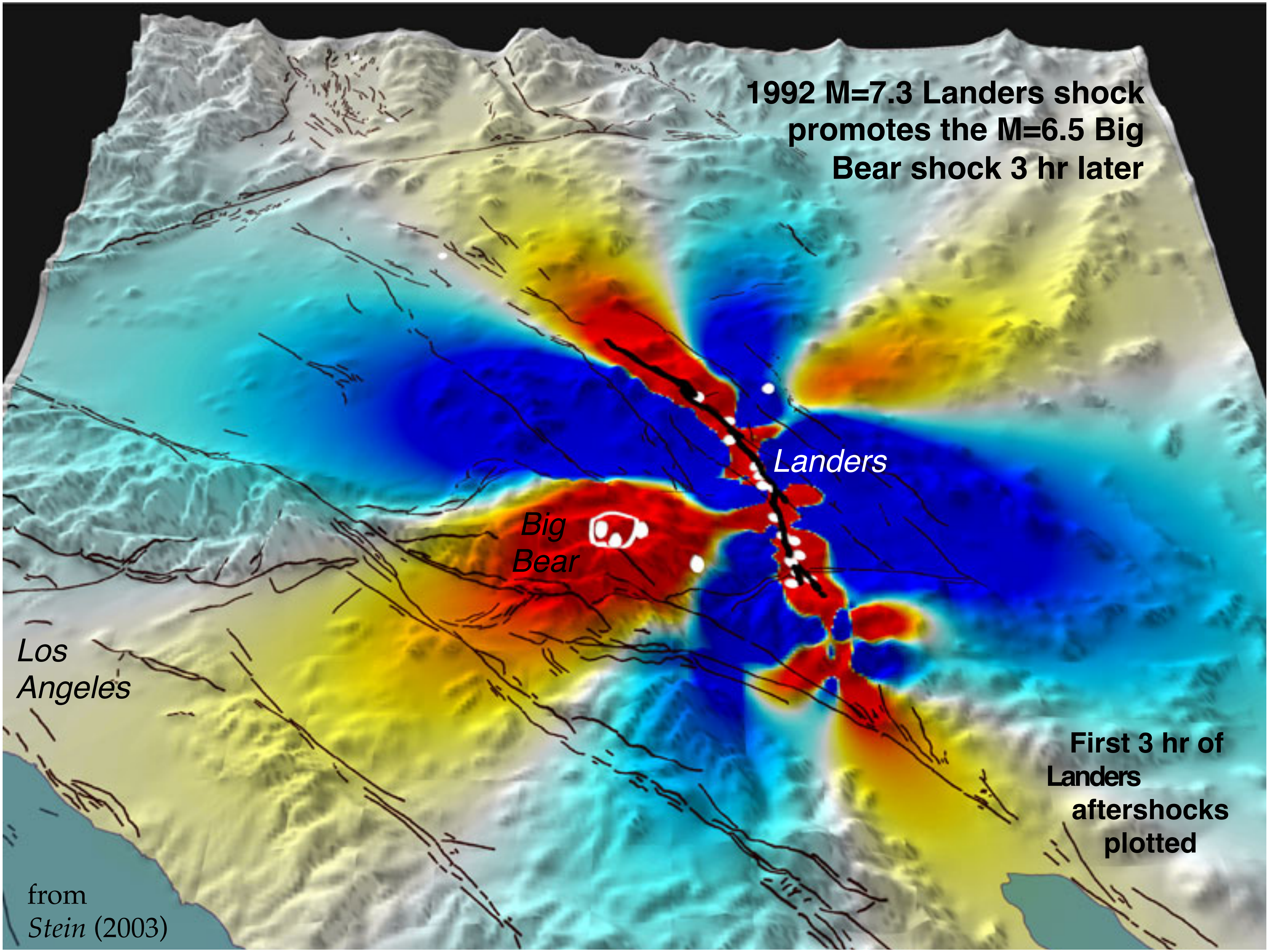
Coulomb stress change (bars) at 10 km depth on Coalinga (*left*) and San Simeon (*right*) rupture planes, for μ=0.8

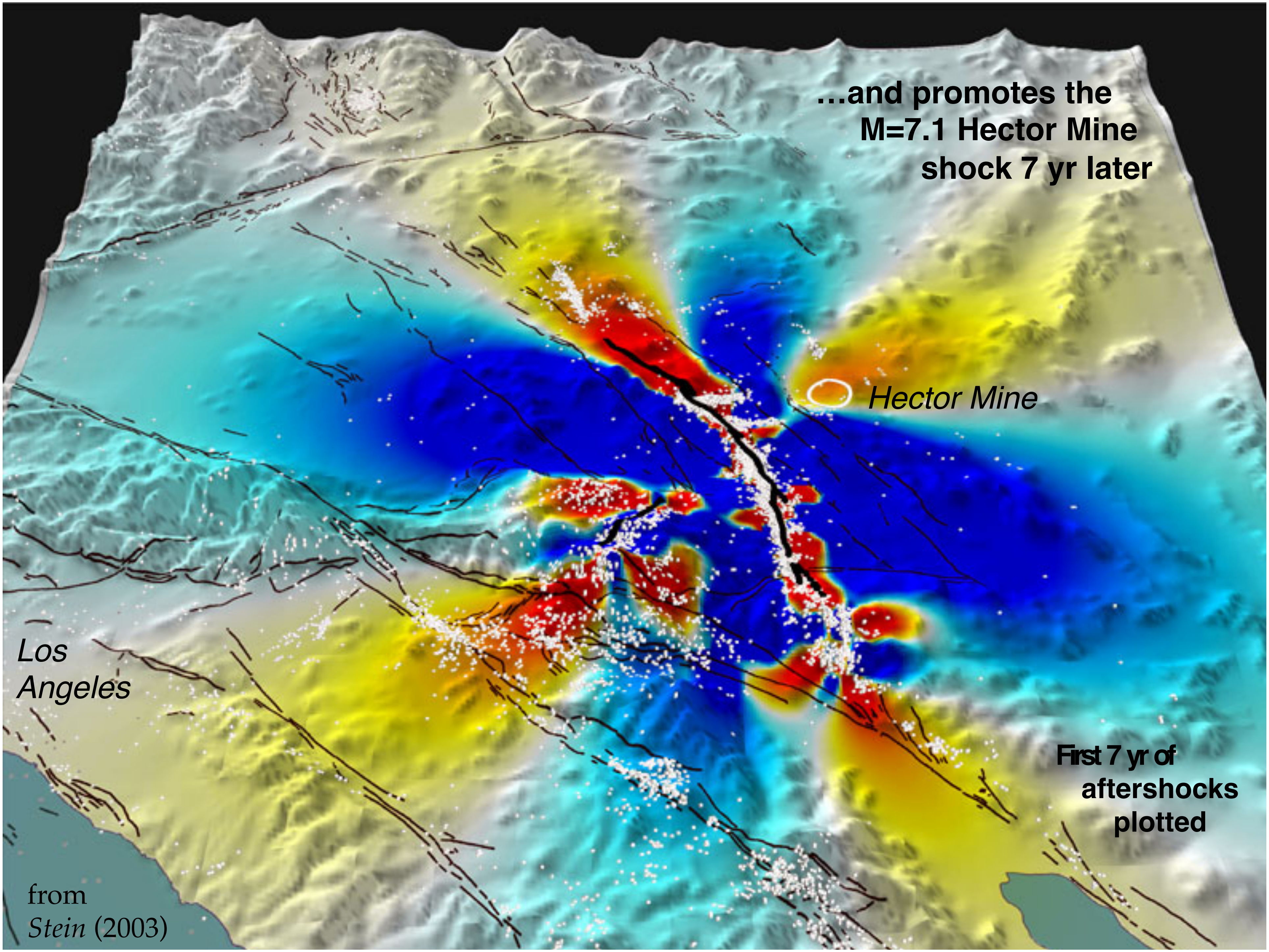


Modified from Lin & Stein (*JGR*, 2004)

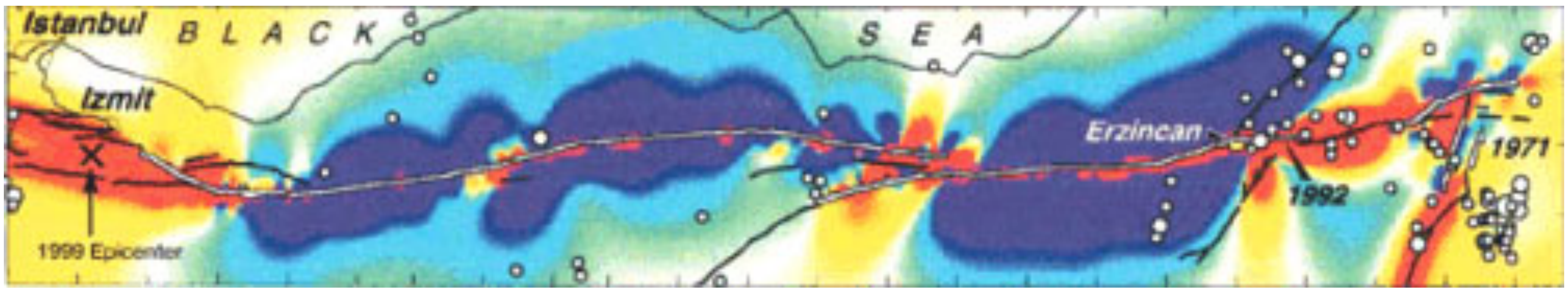
Interseismic stress accumulation model


1992 M=7.3 Landers shock
increases stress
at Big Bear
Landers
Big
Bear
Los
Angeles
First 3 hr of
Landers
aftershocks
plotted
from
Stein (2003)

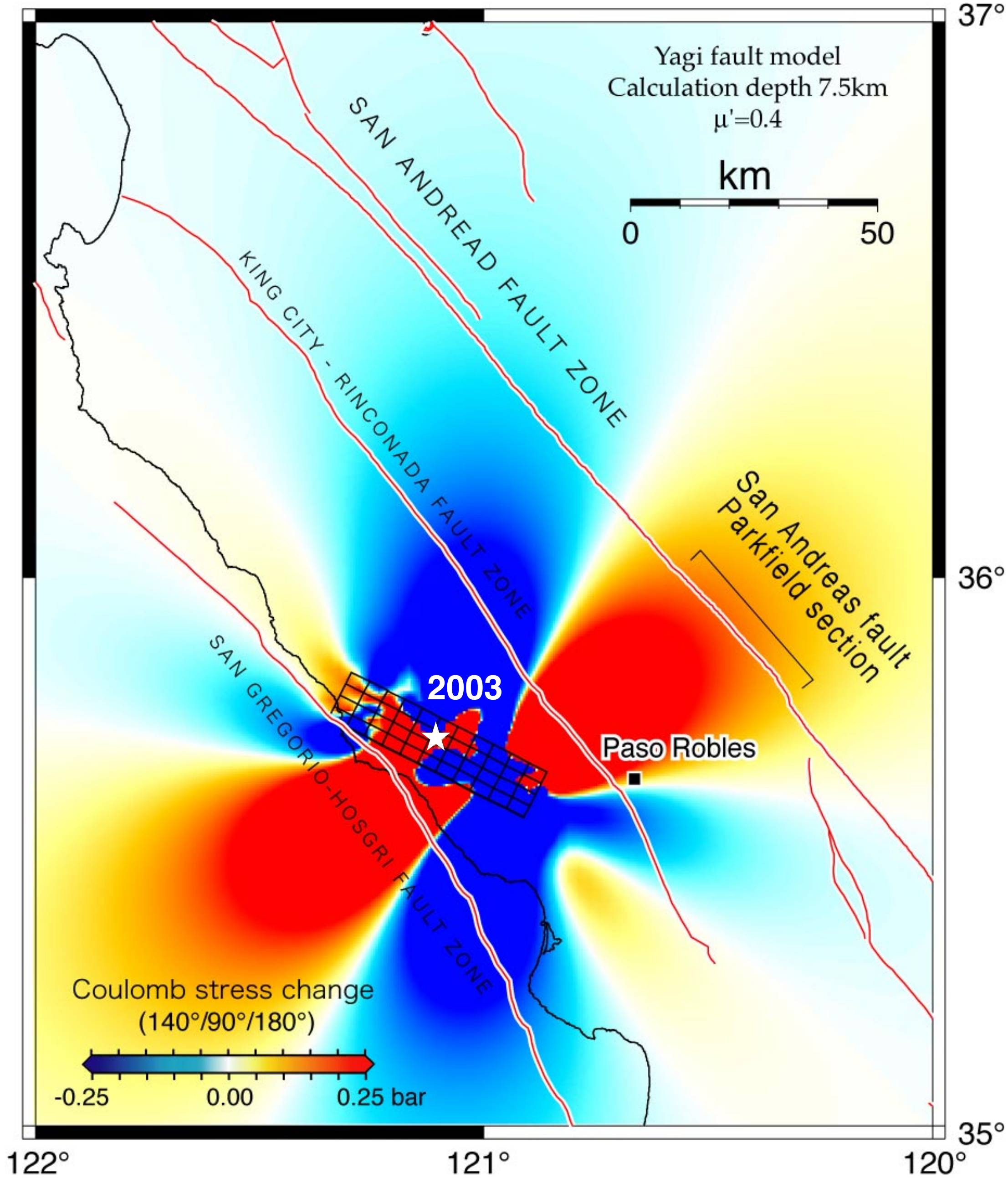

1992 M=7.3 Landers shock promotes the M=6.5 Big Bear shock 3 hr later
Landers
Big Bear
Los Angeles
First 3 hr of Landers aftershocks plotted
from Stein (2003)


…and promotes the
M=7.1 Hector Mine
shock 7 yr later
Hector Mine
Los
Angeles
First 7 yr of
aftershocks
plotted
from
Stein (2003)

North Anatolian fault



- Stress changes calculated for right-lateral faults paralleling the North Anatolian fault due to the entire 20th century sequence of earthquakes
- Each earthquake releases stress where it slips, and brings adjacent segment closer to failure

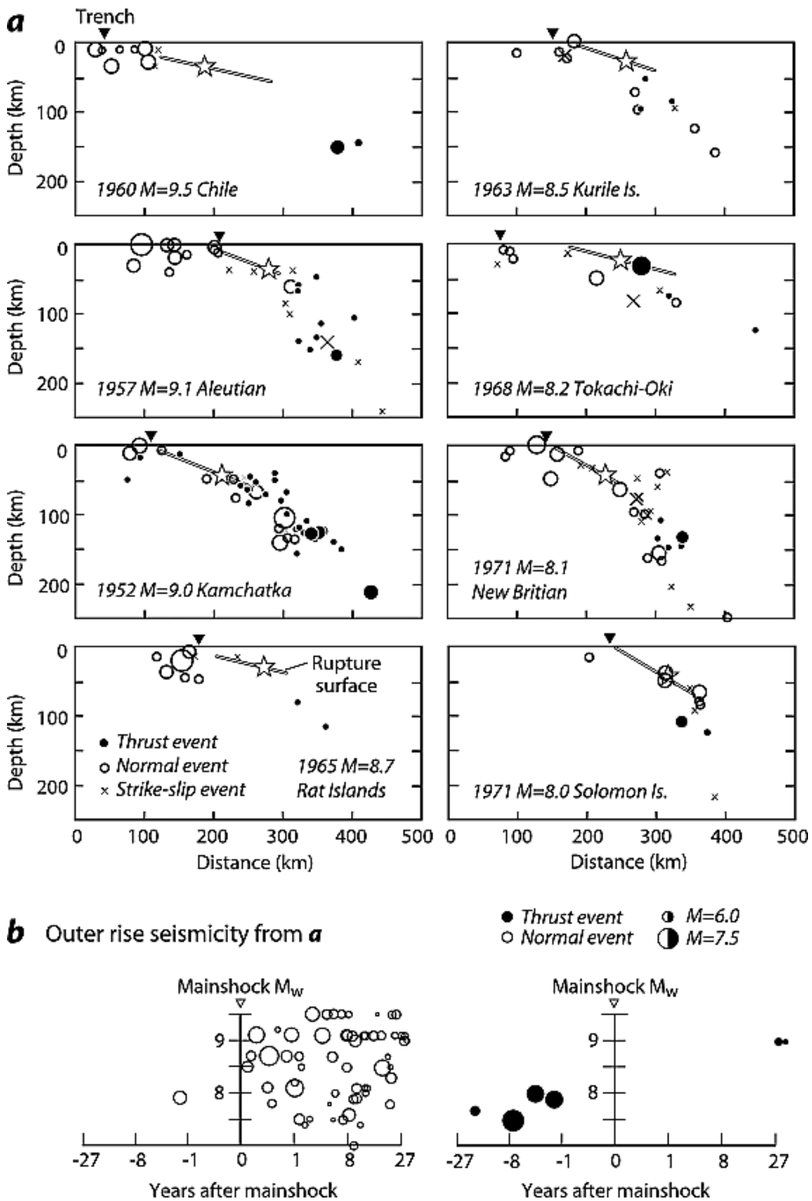


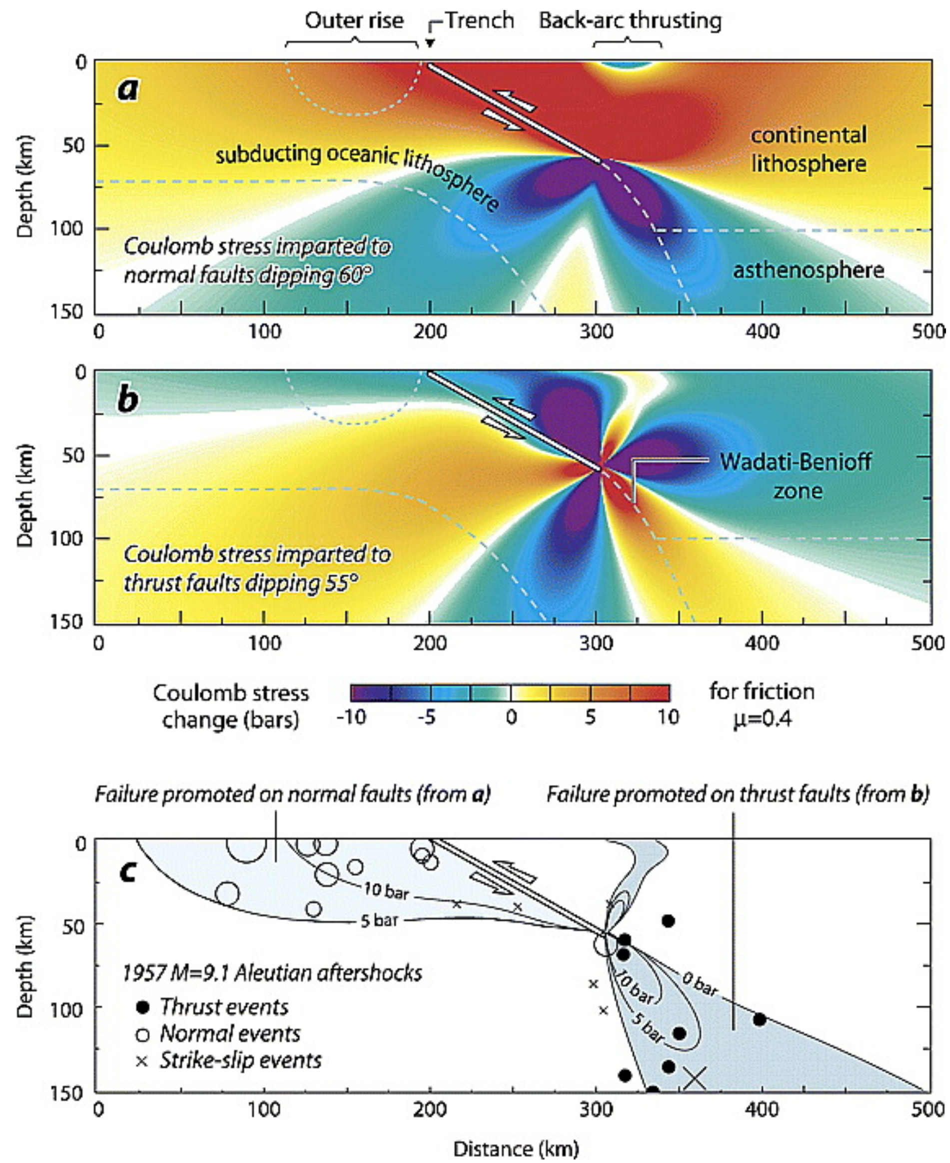
2003 M=6.5 San Simeon earthquake ratcheted up stress at Parkfield

Calculation by
Shinji Toda
on 31 Mar 2004

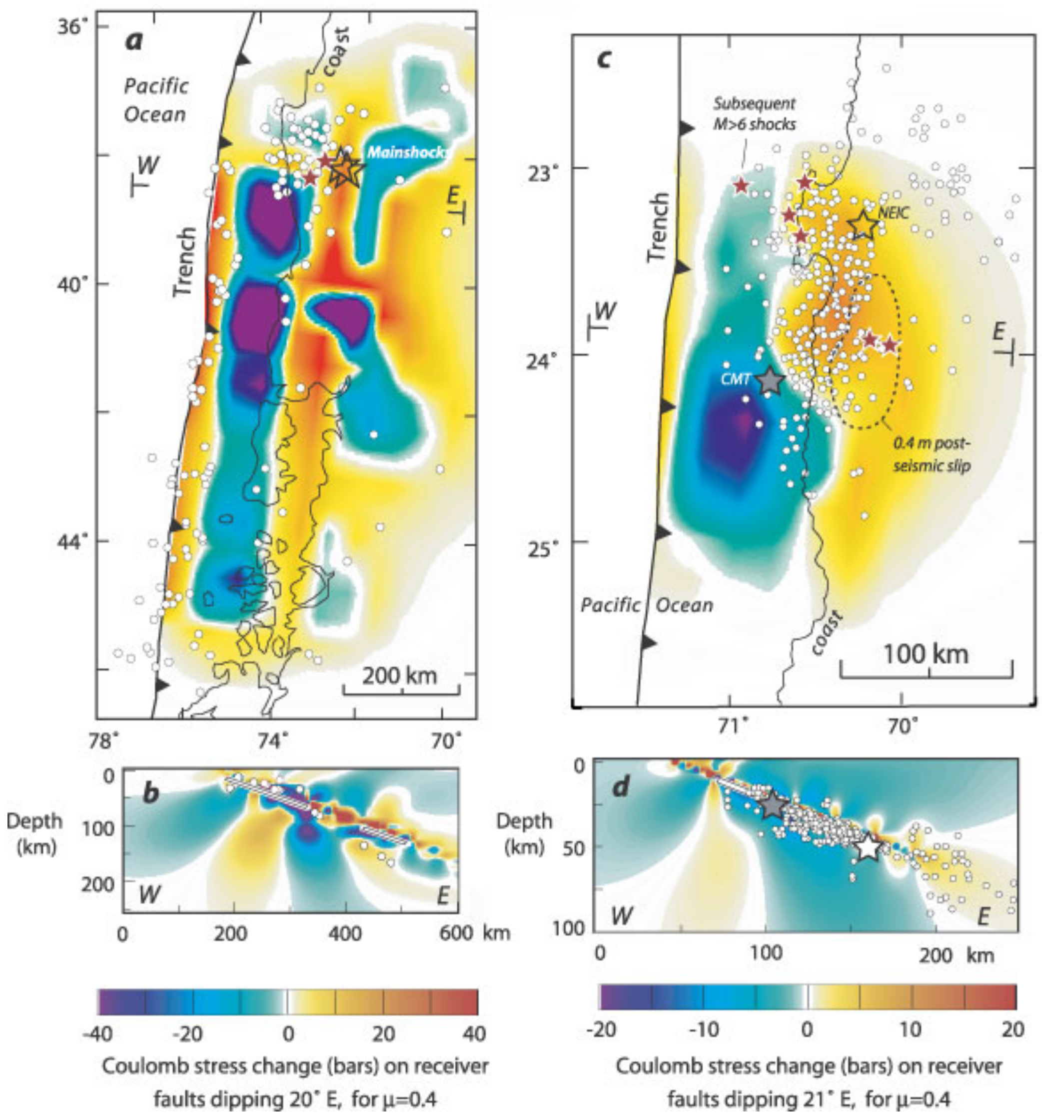
(a similar plot
by Bob Simpson
appears in
Hardebeck et al, 2004)

Stress Transfer at Subduction Zones



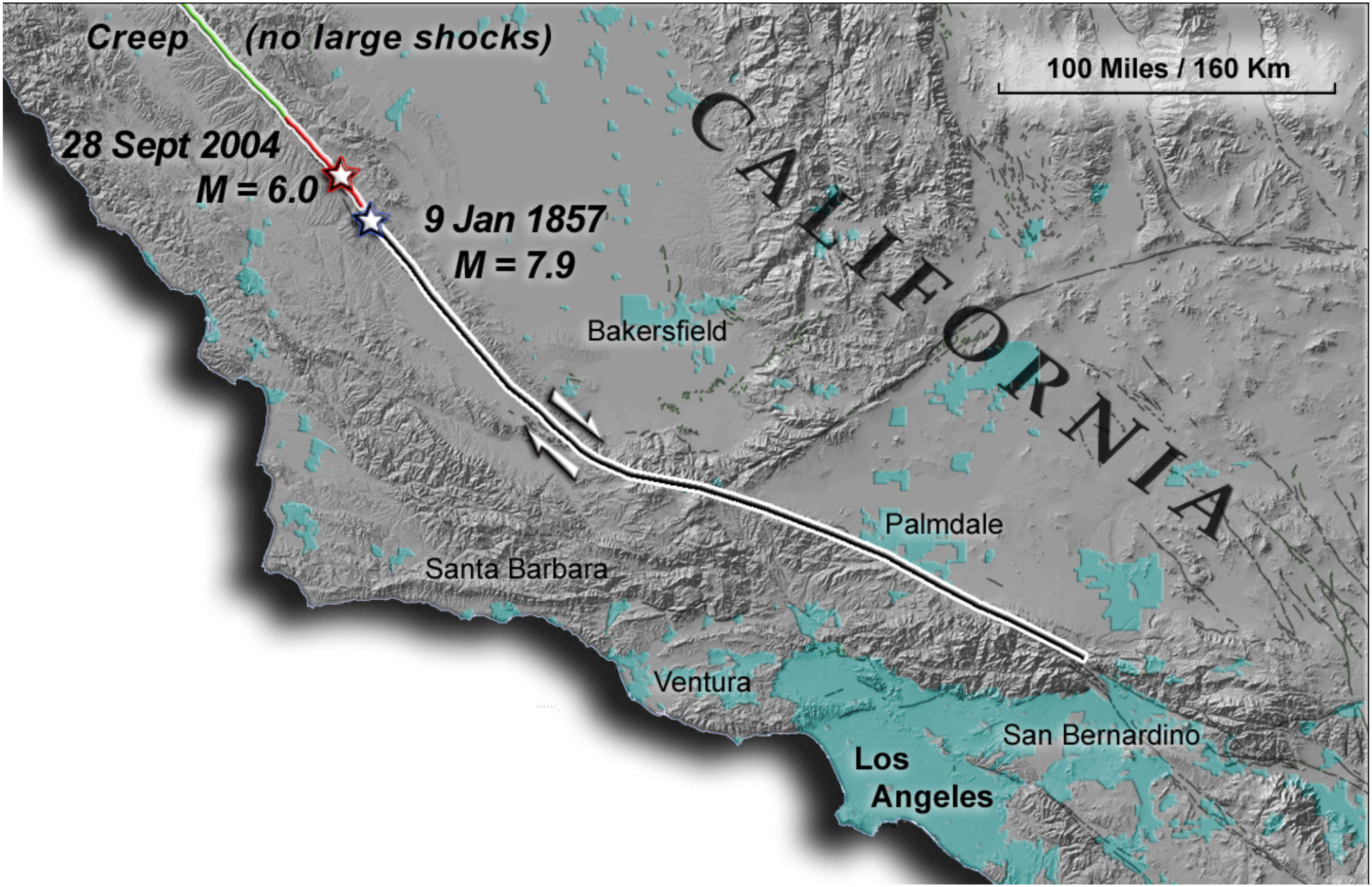


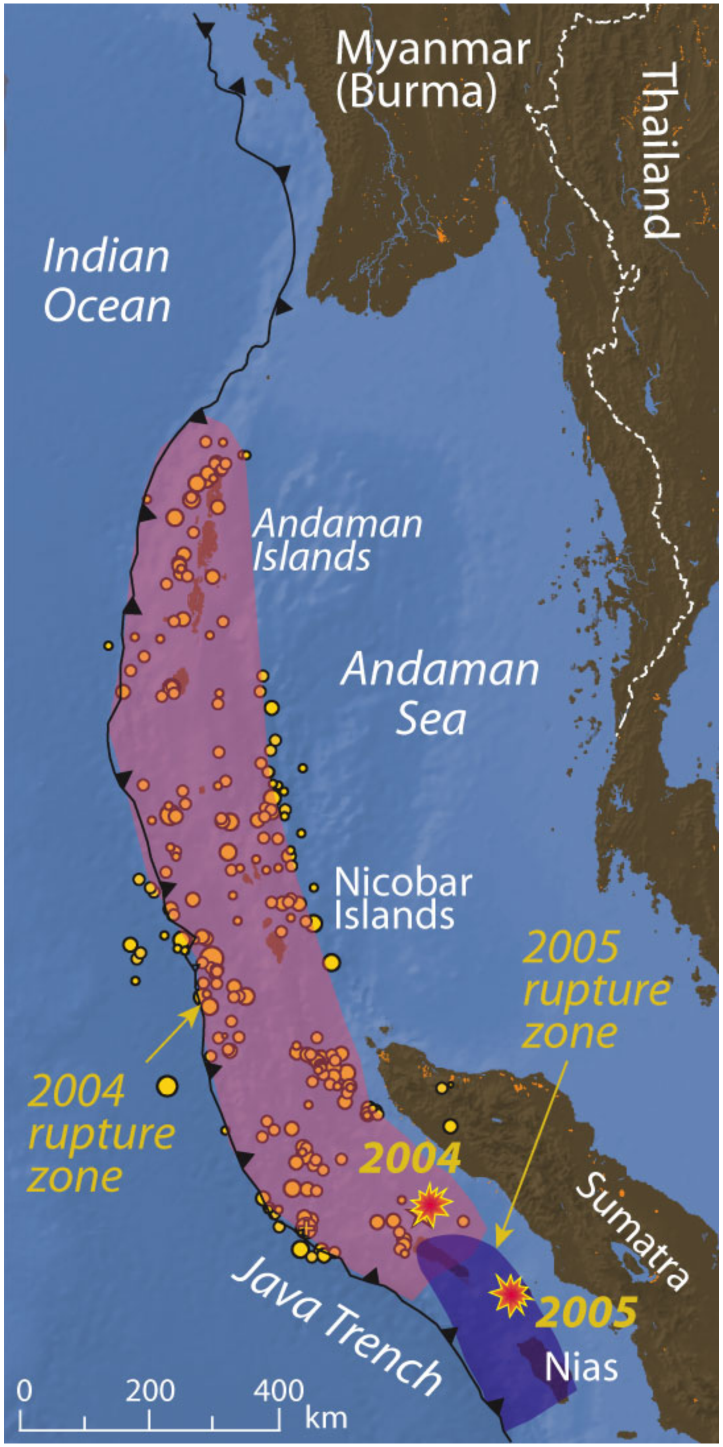
Effect of Large vs. Small Quakes



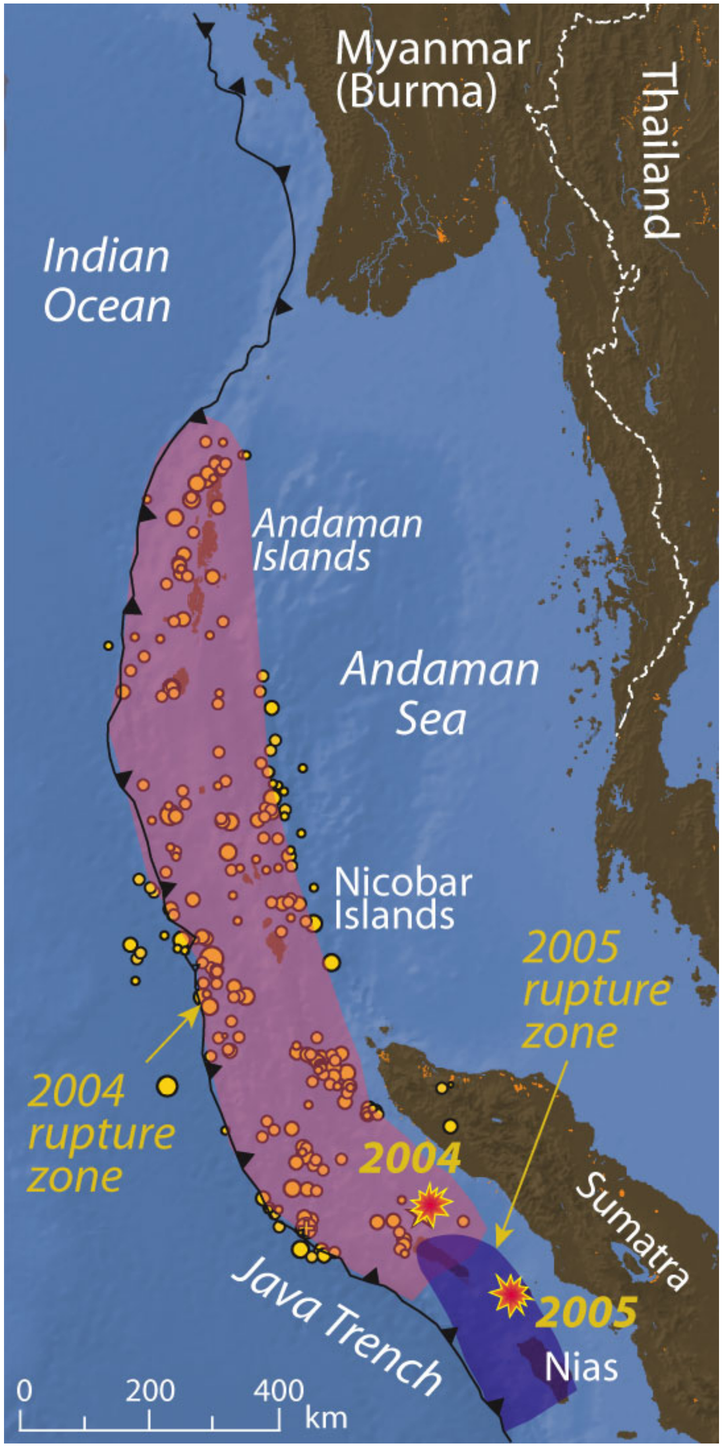
- Compares effect of 1960 Chile with 1995 Antofagasta earthquakes
  - Note difference in color scale

Now what?


Creep
(no large shocks)
100 Miles / 160 Km
CALIFORNIA
28 Sept 2004
M = 6.0
9 Jan 1857
M = 7.9
Bakersfield
Palmdale
Santa Barbara
Ventura
San Bernardino
Los Angeles



Now what part 2?



Now what part 2?